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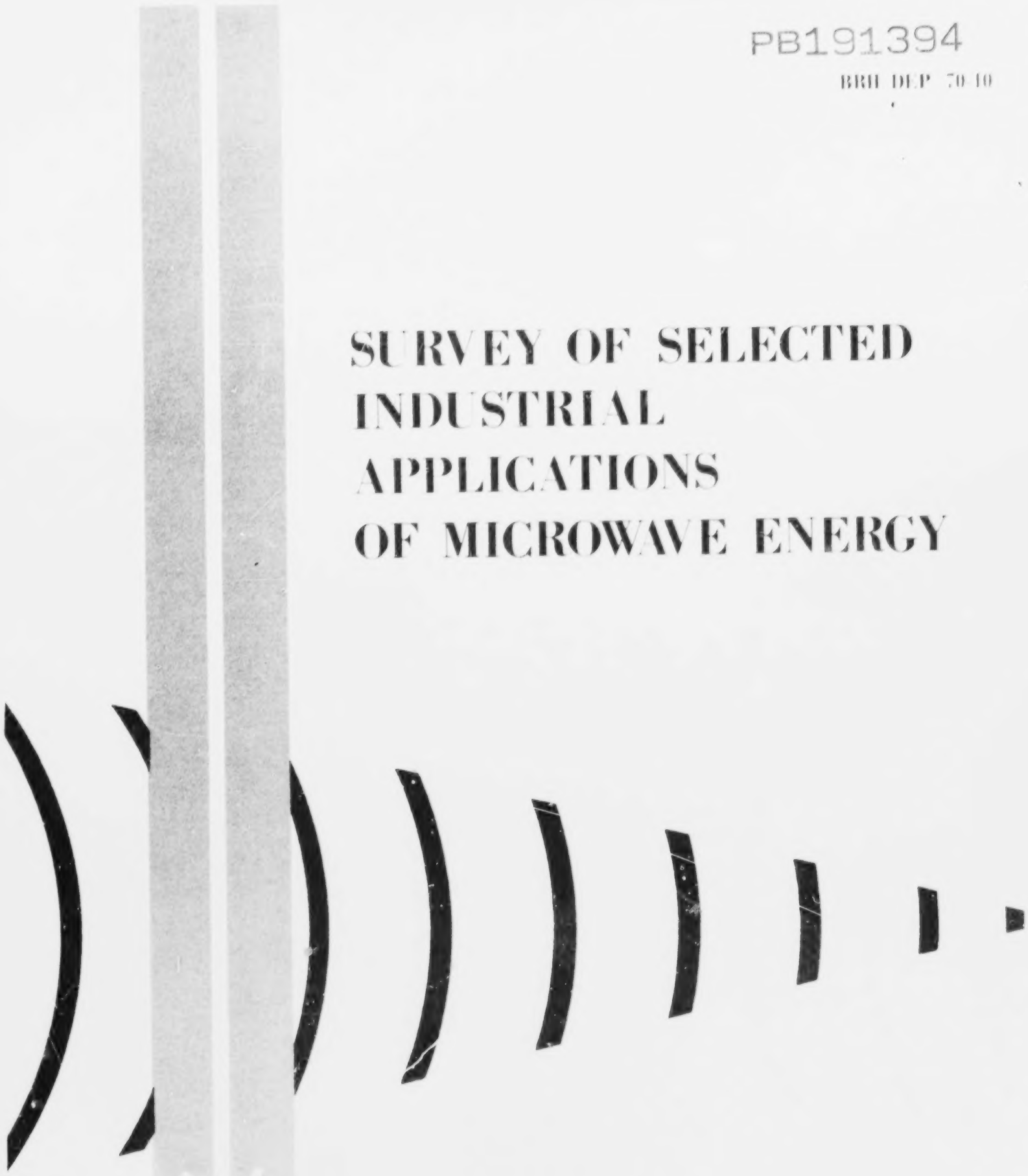
SURVEY OF SELECTED INDUSTRIAL APPLICATIONS OF MICROWAVE ENERGY



U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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DIVISION OF ELECTRONIC PRODUCTS

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SURVEY OF SELECTED INDUSTRIAL APPLICATIONS OF MICROWAVE ENERGY

Division of Electronic Products

May 1970

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
Bureau of Radiological Health
Rockville, Maryland 20852

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FOREWORD

The Bureau of Radiological Health, formerly the National Center for Radiological Health, continues to carry out a national program designed to reduce the exposure of man to hazardous ionizing and nonionizing radiation.

Within the Bureau, the Division of Electronic Products (1) develops and administers performance standards for radiation emissions from electronic products, (2) studies and evaluates emissions of and conditions of exposure to electronic product radiation and intense magnetic fields, (3) conducts or supports research, training, development, and inspections to control and minimize such hazards, and (4) tests and evaluates the effectiveness of procedures and techniques for minimizing such exposures.

The Bureau publishes its findings in Radiological Health Data and Reports (a monthly publication), the Environmental Health Series, Public Health Service numbered reports, appropriate scientific journals, and Division and Laboratory technical reports.

The technical reports of the Division of Electronic Products (DEP) allow comprehensive and rapid publishing of the results of intramural and contractor projects. The reports are distributed to State and local radiological health program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the Clearinghouse for Federal Scientific and Technical Information.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

This report on industrial applications of microwaves has been compiled at the request of the Technical Electronic Product Radiation Safety Standards Committee. Its primary function is to point out the types of equipment being developed by this young industry and the uses to which microwave energy is being applied. Many photographs have been included in the report in order to present as complete a view as possible of various equipment designs and applications. In addition, because the Committee's main interest is safety, considerable emphasis has been placed on the safety features which have been built into this equipment to prevent the occurrence of possible serious accidents.

The manufacturers of industrial microwave equipment have been most cooperative throughout the researching of this paper by providing technical information and photographs of their equipment, and their assistance is greatly appreciated.

Robert L. Elder

Robert L. Elder, Sc.D.
Acting Director
Division of Electronic Products

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ABSTRACT

A survey was made of the industrial applications of microwave energy. This report reviews some of the features of microwave processing, describes the types of industrial microwave equipment, and discusses the uses to which microwave energy is being applied. Considerable emphasis is placed upon the safety features built into the equipment, and recommendations are made for ensuring that the radiation leakage levels do not exceed the design limits.

SURVEY OF SELECTED INDUSTRIAL APPLICATIONS OF MICROWAVE ENERGY

1. INTRODUCTION TO MICROWAVE PROCESSING

1.1 BACKGROUND

After a quarter century of little use in industrial processing, microwave energy has now been developed to a point where it can economically compete with and complement conventional heating systems in industrial processes. The purpose of this report is to examine the equipment, industries, and uses for which microwave energy is now being employed. General conclusions can then be drawn regarding possible health hazards to personnel working near this equipment, the number of people occupationally exposed to radiation from it, and what to expect in the way of future developments in the industrial microwave field.

The following paragraphs point out some of the features of microwave processing; the major manufacturers; the variation of heating with frequency, power, and material; and some economic and quality control benefits which enable microwave heating and drying to compete with conventional thermal systems.

1.2 DEFINITION OF INDUSTRIAL APPLICATIONS

Since this report deals only with industrial applications of microwaves, it is necessary to define what is meant by an "industrial" application as opposed to a "commercial" or "domestic" one. The manner in which the equipment is used largely determines its classification. An industrial microwave unit is one which is designed for use in manufacturing processes and is most often conveyorized to permit rapid, continuous processing. Contrasted with this are the "domestic" unit, the small, closed-cavity ovens found in homes, and the "commercial" oven which is similar to those used in homes but located in restaurants and cafeterias. A major difference between the classifications concerns the operators of this microwave equipment. The average housewife and cafeteria patron know little about the operation of the microwave oven. In industrial applications, however, where an untrained operator can destroy a $100,000 investment,

far greater care is taken to educate personnel in safe operating procedures.

1.3 POWER LEVELS

The output power of an industrial microwave unit depends on the application. It can vary from several hundred watts to several hundred kilowatts, depending on the size, dielectric properties, volume, and rate of material being processed. One would expect a machine designed to dry thin strands of chemical fiber to require less power, for example, than one designed to dry large sheets of hardwood. Then too, a machine which processes 500 feet of fiber per minute would be less powerful than one which processes 2,000 feet per minute, because the rate at which energy is absorbed is lower. Many factors must be considered and compromised to determine the power level at which a machine operates. Several of these factors which affect the material itself, including penetration depth and power dissipation per unit volume, are discussed in appendix A.

1.4 OPERATING FREQUENCIES

Industrial microwave equipment is restricted to the Federal Communications Commission-allocated Industrial, Scientific, and Medical (ISM) frequency bands. These bands are listed in table 1.

Table 1. Industrial, Scientific, and Medical (ISM) frequency bands (1,2)

Radio frequencies	Wavelength (meters)
13,560 kHz ± 6.78 kHz	22.1
27,120 kHz ± 160.0 kHz	11.1
40,680 kHz ± 20.0 kHz	7.4
Microwave frequencies	**Wavelength (cm)**
915 MHz ± 25 MHz	32.8
2.45 GHz ± 50 MHz	12.2
5.8 GHz ± 75 MHz	5.2
22.125 GHz ± 125 MHz	1.4

For various mechanical and technical reasons, the only bands currently being used by industrial microwave manufacturers are those at 915 and 2450 MHz. Figures 1 and 2 show two representative industrial units, the former operating at 2450 MHz and the latter at 915 MHz. Electrically bulky materials such as hardwood generally require the greater penetration depth of 915 MHz to be uniformly processed, whereas electrically thin materials such as paper are more easily handled with the less penetrating 2450-MHz frequency. The preceding is by no means a hard and fast rule, and numerous exceptions are made depending on the manufacturer's preferences and available generating sources.

1.5 MANUFACTURERS AND SALES

Because of the infancy and presently specialized nature of industrial microwave equipment, the number of manufacturers in the U.S. is limited. The major producers of such equipment are listed below.

Bechtel Corporation, San Francisco, California
Cryodry Corporation, San Ramon, California
Genesys Systems, Mountain View, California
Holaday Industries, Hopkins, Minnesota
Raytheon Company, Waltham, Massachusetts
Reeve Electronics, Chicago, Illinois
Varian Associates, Palo Alto, California

Cryodry in 1962 was the first company to introduce a fully conveyorized microwave unit and use water loads at the conveyor openings to control leakage and absorb energy when no material was passing through.

For competitive reasons manufacturers are reluctant to discuss sales and market positions. An inquiry to four of the leading manufacturers[1] resulted in a general consensus, however, that total industry sales for 1969 were in the $1,000,000 to $2,000,000 range. They also agreed that the outlook for the future is quite hopeful since repeat orders are anticipated on several units now in the R&D stage. One manufacturer[2] sees the possibility of annual sales in excess of $100,000,000 by 1975. Others agree that once other industries become convinced of the benefits of microwave processing, then exponential sales growth can be expected.

---

[1] Cryodry Corporation, Genesys Systems, Raytheon Company, Varian Associates.

[2] Genesys Systems, as stated during personal interview with Mr. John Gerling, Vice President-Manager, Industrial Microwave Division, January 7, 1970.

Figure 1. A variable power microwave oven for the food industry. (Courtesy Varian Associates)

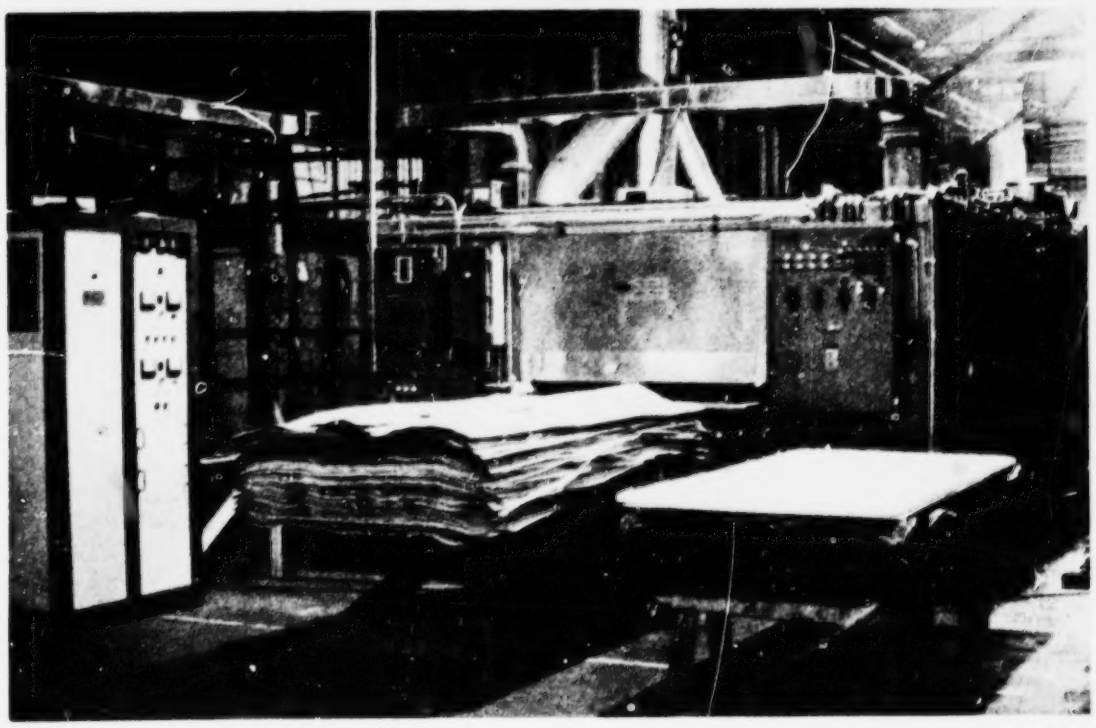


Figure 2. A 50-kW 915-MHz meandering waveguide veneer redryer. (Courtesy Cryodry Corporation)

1.6 ADVANTAGES OF MICROWAVE PROCESSING

As mentioned earlier, microwave processing is very useful in heating and drying many different materials. This fact alone, however, is not sufficient to induce every manufacturer with a heating or drying operation to install microwave equipment. More conventional methods, such as forced hot air or huge batch ovens, have been doing a satisfactory job of heating for some time. Manufacturers are understandably reluctant to scrap their present apparatus for an unproven $100,000 microwave unit unless they are convinced that the microwave unit can do a noticeably better job for the same cost, or the same job for a noticeably lower cost.

Microwave processing does have several advantages over conventional systems and could be suitable to manufacturers for any of the following reasons:

(1) The product cannot be produced in any other way.

(2) Only microwaves will permit the process under consideration to be conveyorized, thus decreasing production time and costs.

(3) No long warmup or turnoff time is required, which can be especially timesaving in cooking applications.

(4) The overall system operating costs are lower.

(5) Higher efficiency (up to 80 percent from source to product) results in less wasted energy and faster processing.

(6) The microwave process can be more accurately controlled than conventional thermal methods because of the accurate selection of frequency, power, and exposure time, and also because of the instant on-off capability should the process need to be interrupted.

(7) Microwave equipment takes up less space than conventional equipment.

(8) Microwave equipment is easier to maintain and clean, especially in certain food industry applications such as poultry cooking.

(9) High operating efficiency wastes less energy heating the plant instead of the product, thereby permitting substantial savings on air conditioning costs.

(10) A combination of several of the above features results in a more economical production system.

The attributes of microwave processing outlined above, while economically justifying, presuppose that a major engineering problem has already been solved; namely, that a microwave system can be designed to process the desired material. This solution generally consists of three parts:

(1) The dielectric properties of the material being processed must be studied to ascertain whether microwave energy can solve the problem.

(2) A suitable system must be designed to carry the product in and out of the chamber containing the microwave energy. The system should preferably be conveyorized for rapid processing, but can have only limited sized openings at the entrance and exit to prevent excessive radiation leakage.

(3) A suitable applicator must be designed which will distribute energy evenly across the product as it passes through the chamber.

Several techniques used by microwave manufacturers to solve these problems are described in the following sections.

2. INDUSTRIAL MICROWAVE EQUIPMENT

2.1 DESIGN CRITERIA

In designing an industrial microwave system, an engineer must decide three major questions: first, what tubes to use as a generating source; second, what type of applicator will best process the material under consideration; and third, how to enclose the applicator system so that material can be continually processed, equipment easily cleaned, and yet radiation leakage limited to a safe level at all times. The following sections examine each of the above areas, pointing out the advantages and limitations of the most common devices and techniques used today by industrial microwave manufacturers in the design of their equipment.

2.2 GENERATING TUBES

The generating tube is the heart of an industrial microwave system. It must supply continuous, stable, long-lived power to the system at the power levels required by the application. Not until the past decade have reliable tubes capable of emitting 5 kilowatts to 100 kilowatts of continuous power become available; this type is most useful in industrial processing systems. The most common tubes used today in industrial systems are summarized in table 2. Only those tubes with powers above 2 kilowatts have been included because almost all industrial systems constructed to date have had output powers above this level. Table 2 lists three different types of tubes: magnetron, klystron, and amplitron. For operation at 915 MHz, the only tubes used in industrial applications are magnetrons, whereas all three are available at 2450 MHz. The operating features of each are summarized below.

The amplitron (fig. 3), designed and patented by Raytheon Company, is the most powerful tube listed in table 2, but is also the most complex to operate and costly to purchase. A typical 100-kW tube will cost between $12,000 and $15,000. Gerling (3) has pointed out that the amplitron requires rather complex circuitry for reliable operation as well as a high-pressured cooling system within the tube. On the plus side, the amplitron is probably the most efficient tube in the table with ordinary operating efficiencies around 70 percent and an operating lifetime in excess of 10,000 hours.

Table 2. Common tubes used in industrial microwave equipment

Manufacturer	Type	Model	Frequency (MHz)	Power (kW)
American Microwave	Magnetron	XL-82	2450	2.5
Amperex	Magnetron	YJ-1191	2450	5
Amperex	Magnetron	YJ-1160	2450	2.0-2.5
EEV	Magnetron	BM25L	915	20-25
Eimac-Varian	Magnetron	EM15LS	915	25
Eimac-Varian	Klystron	5K70SH	2450	30
General Electric	Magnetron	ZM-6134	915	18
Litton	Magnetron	L3858	2450	2.5
Litton	Magnetron	L5D46	2450	10
RCA	Magnetron	8684	915	30
Raytheon	Magnetron	QKH-1536	915	50
Raytheon	Amplitron	QKS-1261	2450	10-100

Figure 3. Raytheon model QKH-1536 S-band amplitron.
(Courtesy Raytheon Company)

The klystron, invented by the Varian brothers in the late 1930's, is similar to the amplitron in output power, but is less efficient as well as less costly. A typical 30-kW tube will cost from $5,000 to $7,000 and will operate at or near 50 percent efficiency. The life expectancy is 3,000 to 5,000 hours, somewhat less than that for the amplitron. Klystrons are considerably easier to cool, however, because of the linear geometry of the cavities, and stable operation is also easier to maintain. The klystron is the most popular high-powered tube and is widely used in radar defense systems where powers soar to as high as 2.5 MW.

The magnetron, the most recent member to the medium-powered (above 10 kW) and high-powered (above 25 kW) tubes, is the most popular generating source in today's industrial microwave systems because of its low cost, broad bandwidth, high efficiency (60 percent typical) and reliable stability. A typical 2.5-kW magnetron will cost between $250 and $500, while a more powerful 30-kW tube will sell for about $2,200. Table 2 points out that for industrial systems requiring less than 30 kW, magnetrons are the dominant generating sources.

Because magnetrons with output powers in excess of 10 kW have only recently been perfected, a "modular" approach to system design has been quite popular. In a modular design, as shown in figure 4, a number of low-powered tubes, or modules, are combined to meet a system's power requirements rather than using a single medium- or high-powered source.

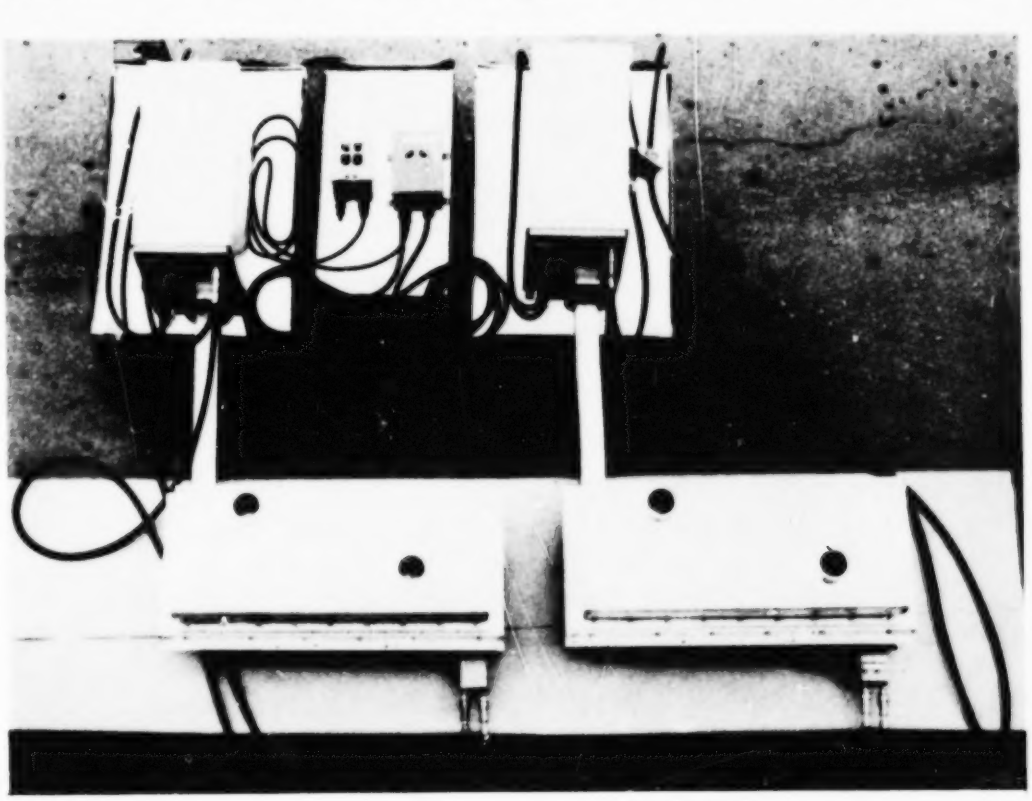


Figure 4. A simple modular system showing power packs and applicators. (Courtesy Genesys Systems)

Numerous justifications for such a modular approach have been set forth by Gerling (3) in an example contrasting a single-tube high-powered system with a comparable-power modular design. These benefits include reduction of hot spots, lower harmonic generation, lower inventory costs, less system downtime when a tube failure occurs, lower amortization costs, and greater system programming capability.

A modular approach is not restricted to magnetrons alone but can be employed with any of the tubes mentioned in table 2, depending on the total system power required. A 120-kW system, for example, could be constructed using a single high-powered tube, forty-eight 2.5-kW magnetrons, four 30-kW klystrons, or any other combination which the design engineer feels will best meet his needs. Such factors as tube availability and reliability often affect this decision, as does the previous success which the manufacturer has had with the various tubes. Opinions vary as to which, if any, approach is optimum for a given application.

2.3 APPLICATOR DESIGNS

The type of applicator used to irradiate a product during processing is largely determined by the product itself. Depending on the geometry of the material, four basic designs are commonly used. They are (1) folded waveguide sections with a conveyor passing through narrow slots in the sides of the guide perpendicular to the direction of energy flow (fig. 8); (2) a circular or rectangular linear section of waveguide with the material conveyed down the guide itself parallel to the direction of energy flow (fig. 11); (3) a multimode cavity either conveyorized for relatively thin objects (fig. 21) or totally enclosed for large bulky products (fig. 16); and (4) a planar fringing field applicator with the product passing either perpendicular or parallel to the direction of energy flow depending on applicator orientation (fig. 24).

2.3.1 Meandering Waveguide

The folded, or meandering, waveguide applicator is most suitable for processing thin sheets since significant leakage occurs from the slots in the guide if they are greater than 30 percent of the wall width. Most rectangular guides have one cross-sectional dimension twice the size of the other and are operated at a frequency such that only one mode, the TE_{10}, will propagate. The electric field pattern and current flow for such a guide are shown in figures 5 and 6 (6).

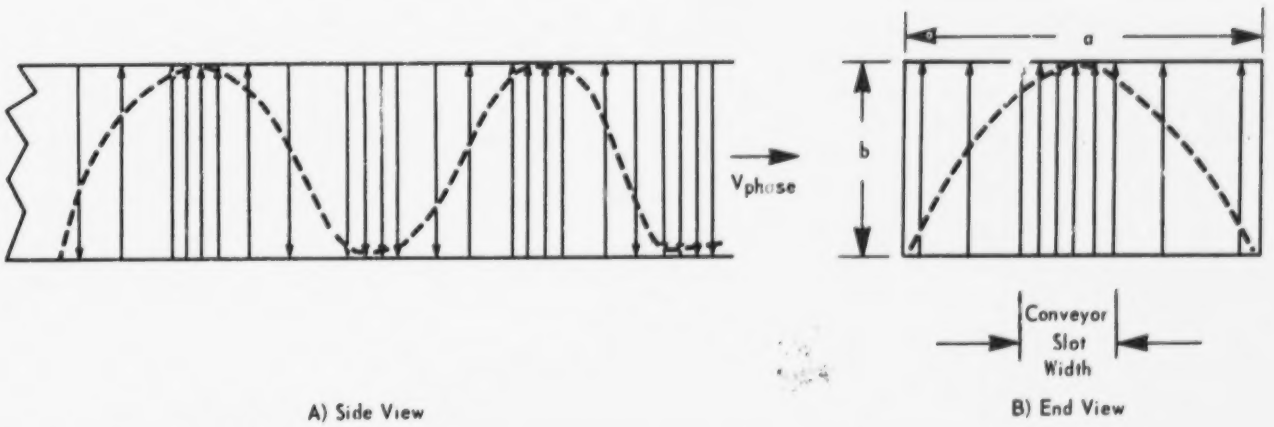


Figure 5. Electric field pattern for TE_{10} mode in rectangular waveguide, showing positioning of conveyor slot in wide walls to intercept peak field strength. (6)

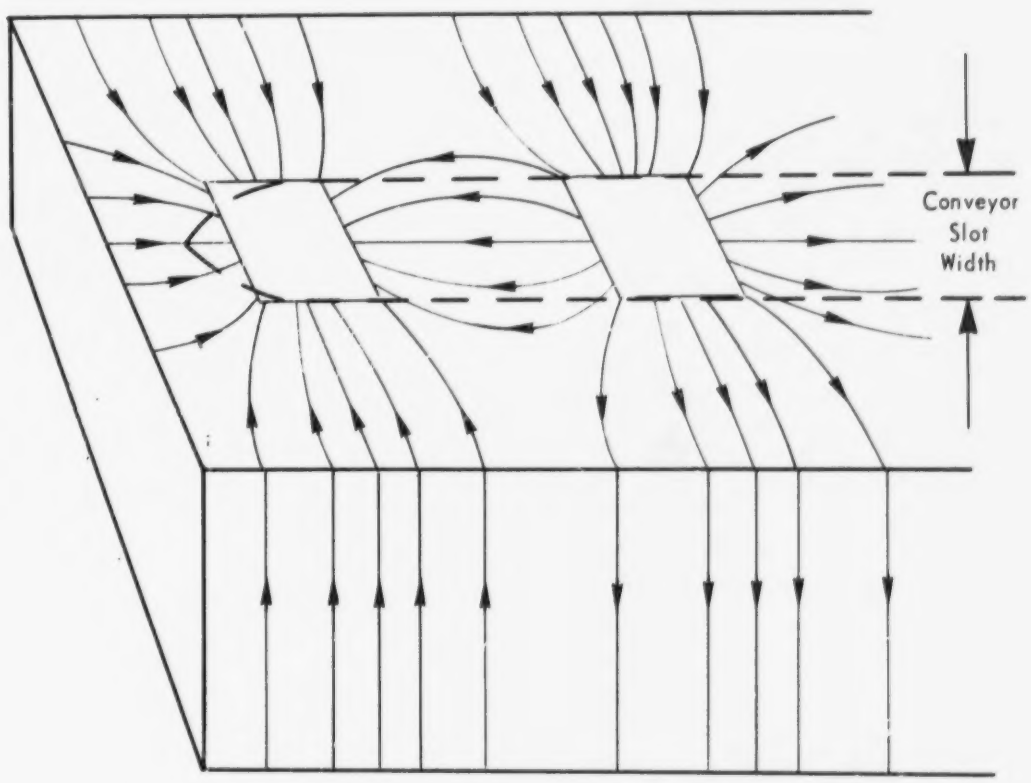


Figure 6. Wall currents for TE_{10} mode in rectangular waveguide, showing slot width to intercept longitudinal currents without disturbing transverse currents. (6)

Note that the electric field strength is confined to the transverse plane, and is maximum at the center of the guide and zero at the side walls; currents, however, flow in two directions, both longitudinally down the center of the wider walls and transversely around the perimeter of the guide. Inspection of figures 5 and 6 shows that if a narrow slot is cut along the length of the guide through the top and bottom walls (outlined in fig. 6), then the peripheral currents will not be greatly disturbed. In addition, the electric field will be a maximum at the slot where the product passes through the guide (fig. 5-B) and will cause the greatest heating. By folding the waveguide back and forth, the product can repeatedly pass through the guide until the fields have been fully attenuated. The dielectric properties and width of the material determine the number of folds which must be placed in the guide to dry the product to the desired final moisture content.

Two adjustments are made in the slot design to prevent unwanted radiation leakage. These are illustrated in figure 7 (2). The first is to add lips to the slot to reflect possible leakage, and the second is to taper the ends of the slot for better impedance matching.

Since it is unlikely that a load will always be passing through the slotted guide, provision must also be made to dissipate the RF energy in a no-load situation. This is accomplished by installing a water load (highly absorbent, K=80) as a termination to the guide with sufficient circulation to absorb all the power generated through the guide without boiling the water. This water load also helps to stabilize load variations caused by varying moisture contents or gaps ir the material being processed.

An example of the folded waveguide dryer is shown in figures 8, 9, and 10. The folded waveguide shown in figure 8 has been molded into two sections to minimize space and provide a built-in cabinet to prevent leakage. Figures 8 and 9 show air vents, made up of waveguide-beyond-cutoff, through which forced air drying can also be applied to the product without RF leakage. Figure 10 displays the assembled system, pointing out the RF entrance port, air fans, water load termination, thinness of the slot width (too narrow for even a finger), and final bolted assembly to prevent accidental opening during operation.

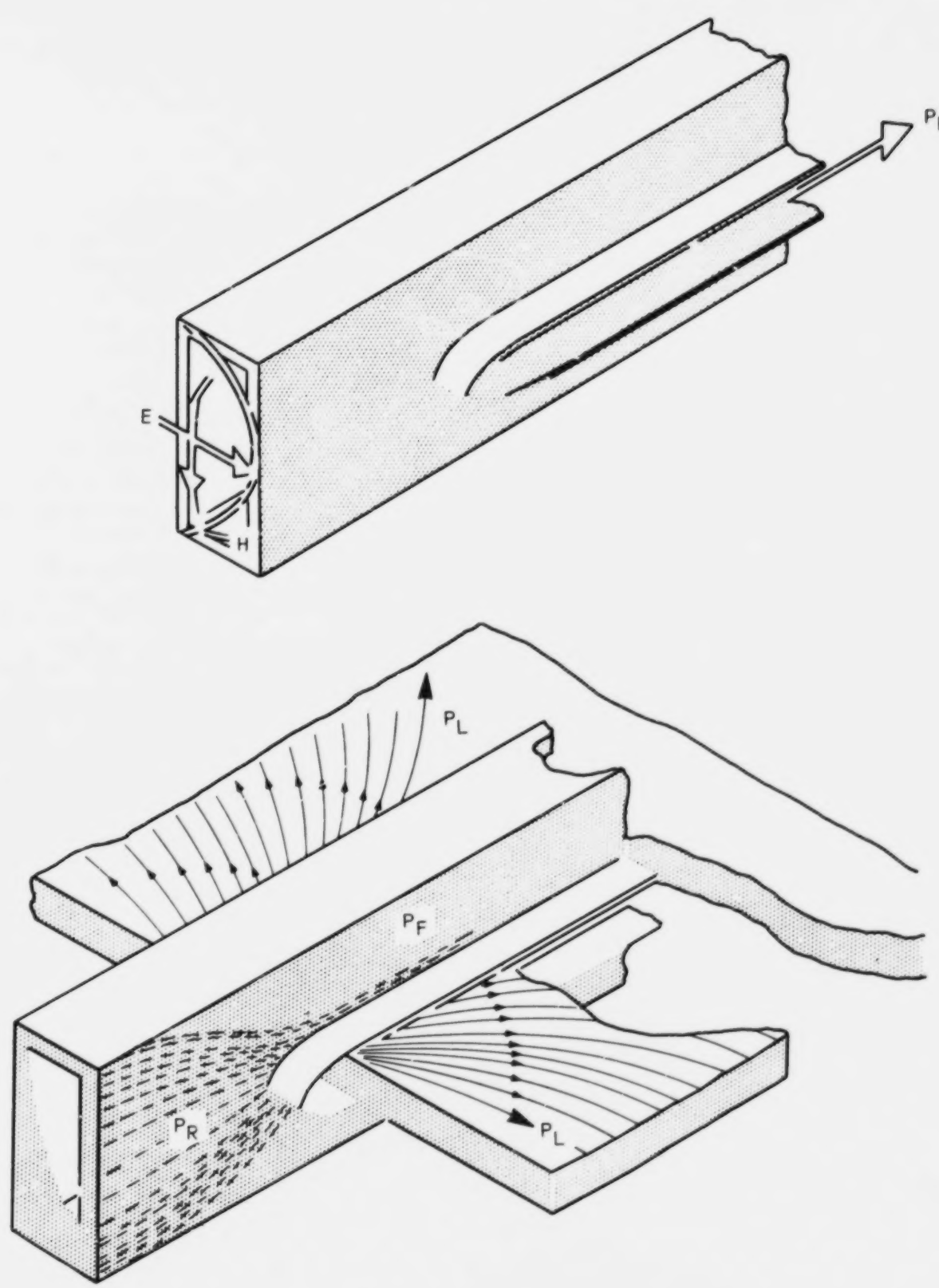


Figure 7. Conveyor slot with tapered ends, showing current pattern in material passing through slot. (2)

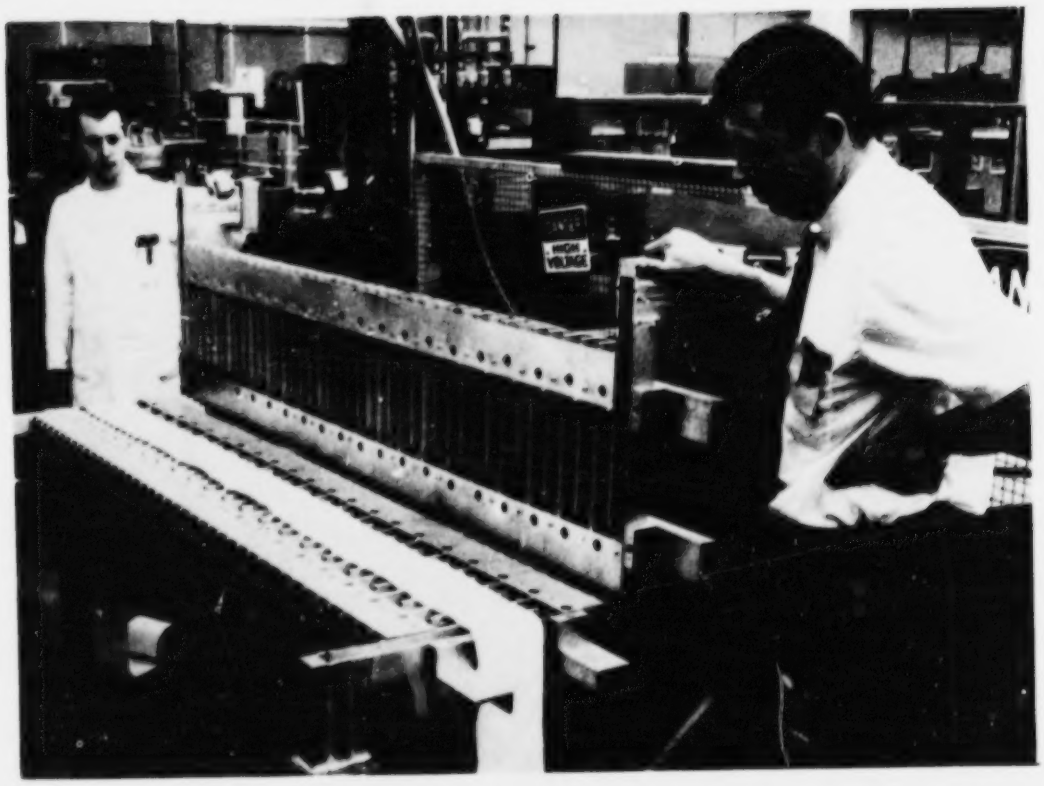


Figure 8. Meandering waveguide applicator for processing thin sheets. (Courtesy Varian Associates)

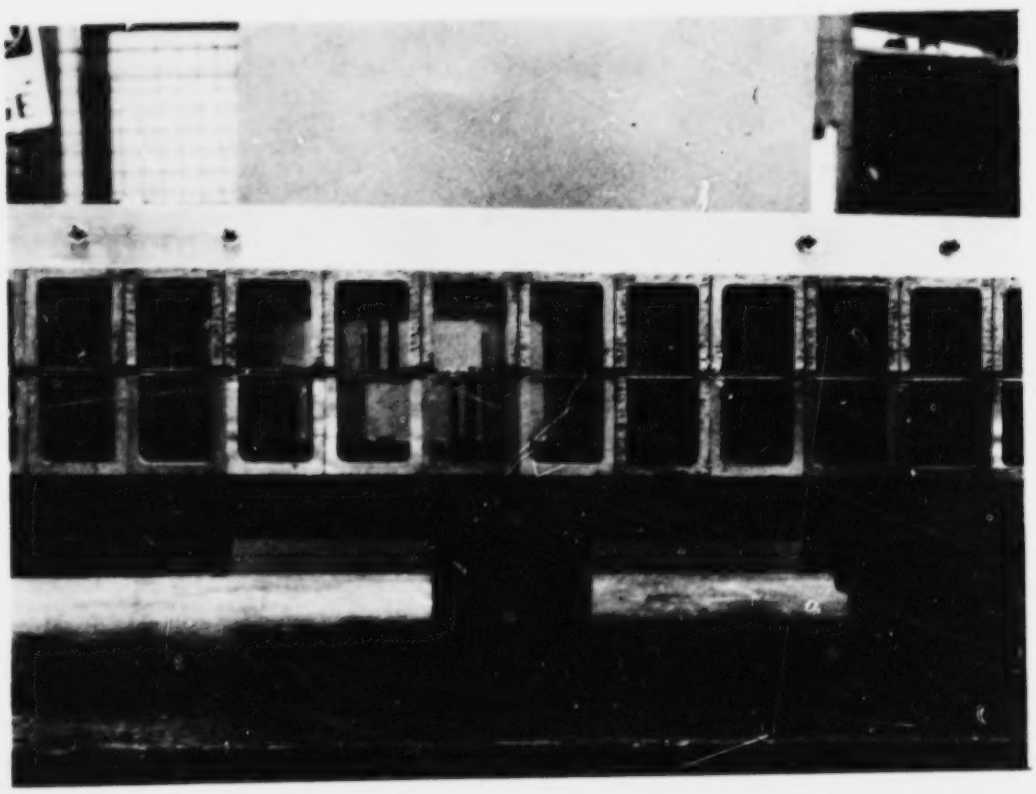


Figure 9. Waveguide-beyond-cutoff air vents for the meandering waveguide applicator of figure 8. (Courtesy Varian Associates)

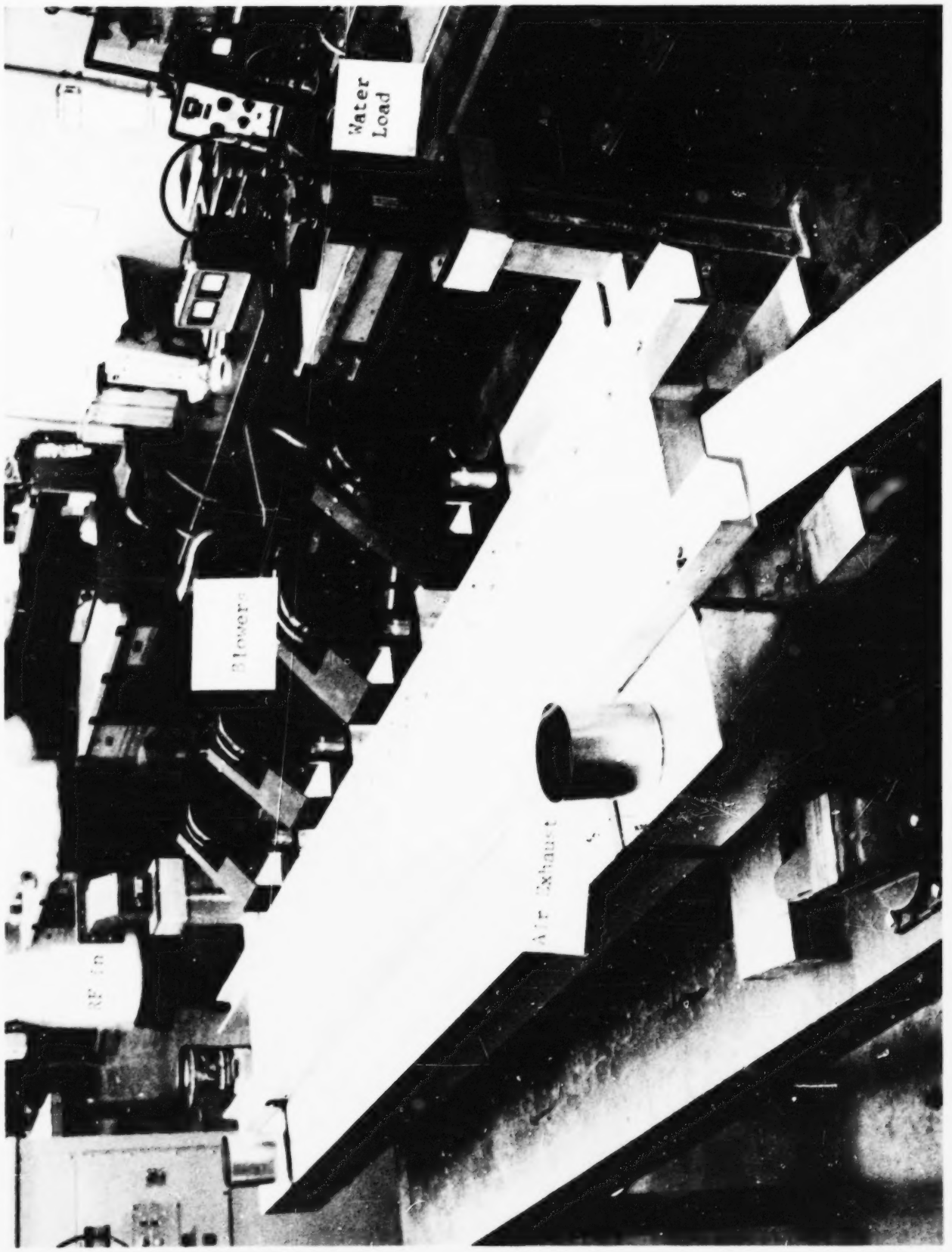


Figure 10. Assembled meandering waveguide applicator. (Courtesy Varian Associates)

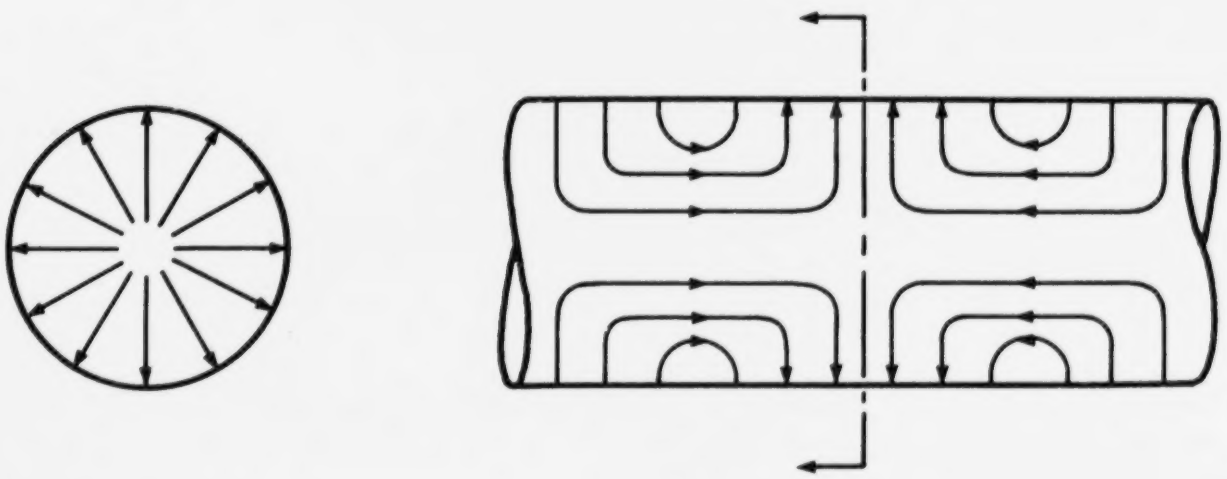
2.3.2 Passage Through Length of Waveguide Section

In addition to running a conveyor perpendicular to the direction of power flow as in the folded waveguide dryer, it is also possible to put openings in the ends of a waveguide section and run a conveyor through the guide parallel to the direction of energy flow. Once again the openings at the ends of the guide must be quite small to prevent radiation leakage, so only thin products can be processed in this way. This applicator differs from the folded guide applicator primarily because the coupling of the electric field to the material is not as strong. This fact is not altogether detrimental, however, because many products such as bacon heat more evenly when they are processed slowly. For such products the poorer coupling is a benefit.

The extreme simplicity of this type of applicator is a big advantage, both in design and cost reduction. Because the guide is fully enclosed, it serves as its own cabinet, and leakage occurs only at the entrance and exit slots. This leakage can be controlled very effectively and economically either by inserting quarter-wave filters outside the slits or by using waveguide-beyond-cutoff as an aperture. Figure 11 shows such a system with a section of circular waveguide-beyond-cutoff serving as entrance and exit avenues for the product. Such a design could be useful in processing thin strands of fiber or the like.

Figure 11. Waveguide section as applicator. (Courtesy Genesys Systems)

A disadvantage of this type applicator is that there is a tendency toward uneven heating because of the varying field pattern across the rectangular guide (fig. 5). The material in the center tends to be more heated than that at the edges. This can be corrected by either altering the shape of the guide to stimulate higher order modes for more even energy distribution or, when processing thin strands, by switching to a circular waveguide operated in the TM_{01} mode for which the field intensity has no circumferential variations (fig. 12).



a. Cross-sectional view b. View along waveguide

Figure 12. Electric field pattern for TM_{01} mode in circular waveguide.

2.3.3 Multimode Cavity

A multimode cavity is suitable for heating an enormous variety of materials from potato chips to massive blocks of frozen beef, primarily because, except for conveyorized units, the size and geometry of the material being processed is restricted only by the size of the cavity.

For a given cavity size the number of possible modes increases with frequency. It is common practice with batch ovens to include mode stirrers to excite as many modes as possible and prevent standing wave patterns from forming, thus distributing the energy more evenly throughout the cavity. In many conveyorized units, however, the motion of the material itself is sufficient to ensure uniform heating.

There are three basic multimode cavity designs in use today: batch, semiautomatic, and fully conveyorized. The difference between the three is the manner in which the material being processed gets into and out of the resonant chamber. In a batch oven, the product must be either manually or mechanically placed into the cavity and a door closed. Such industrial ovens differ from those found in the home in that they are considerably larger, have adjustable power output, and are more ruggedly constructed. The semiautomatic and fully conveyorized units are similar in that they are both conveyorized. The semiautomatic is designed for materials which can be handled by conveyor but are too large to pass through a fully conveyorized system without excessive radiation leakage from the end openings. It has sliding doors at the entrance and exit ports which are periodically opened to allow new material to pass in and processed material to pass out. The fully conveyorized unit is, as its name indicates, a continuous processing system with limited openings at both ends.

2.3.3.1 Batch Ovens

Typical examples of industrial and/or laboratory batch ovens are shown in figures 13 through 17, which illustrate several design and safety features in common use today. The oven shown in figure 13 has a rotating platter as a mode stirrer and a double quarter-wave choke seal at the door. A choke seal is highly effective in preventing radiation leakage since its effectiveness does not depend on a good metal contact between the door and body of the oven, as does the metal pressure seal. It is possible to open the door slightly and still have little leakage.

The door can also become coated with grease or other deposits, as often happens in long-uncleaned ovens, and the seal will still function. The rotating platter prevents hot spots by transporting the product through varying field strengths, thereby distributing the power absorbed. Not visible in the photograph but recessed within the door latch is an interlock to protect the unwary operator who mistakenly opens the door before turning off the power.

Figure 14 points out a different type of mode stirrer and door seal. The mode stirrer acts like a paddle wheel to prevent the formation of standing wave patterns, and permits the material being processed to remain fixed. The metal-to-metal seal is achieved by lining the door with spring-like "finger stock" which maintains pressure between the door and oven. The effectiveness of finger stock in preventing leakage was measured[1] for a 25-kW system and found to be quite

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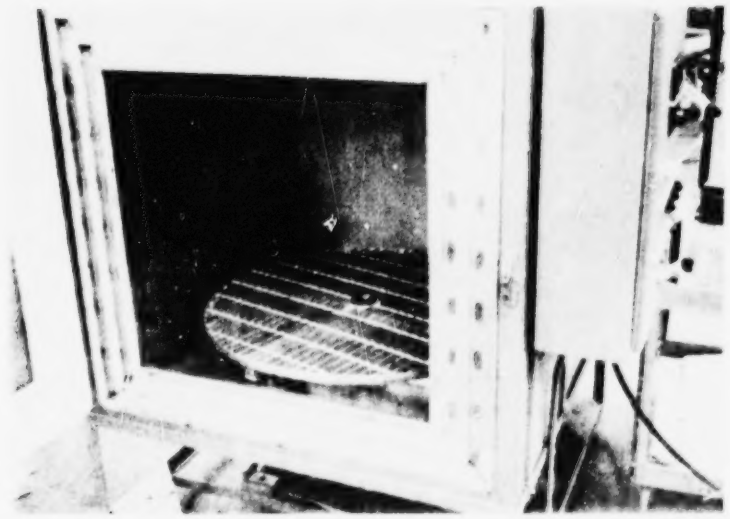
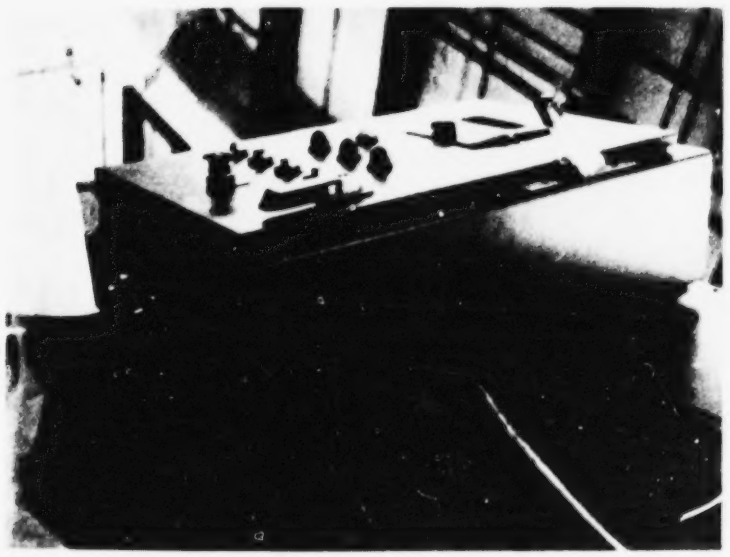
[1]Measurements were made with a Narda 8100 radiation monitor on the side doors of a Cryodry Corporation 50-kW potato chip finish dryer, similar to that shown in figure 31.





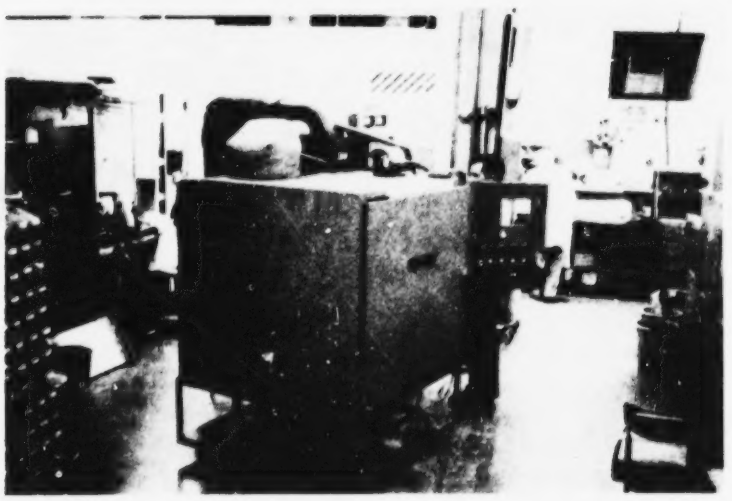


Figure 13. Batch oven showing double quarter-wave choke seal, rotating platter, and control panel. (Courtesy Varian Associates)

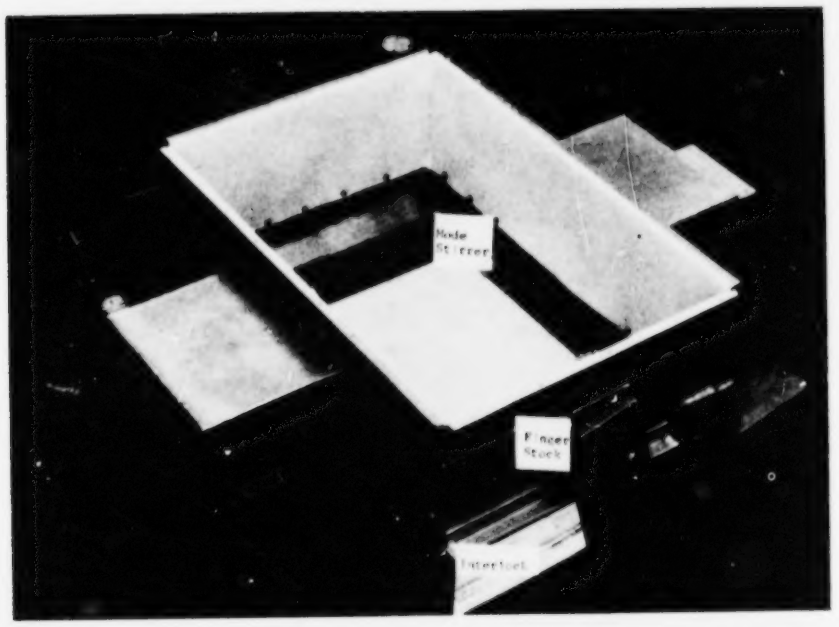


Figure 14. Batch oven showing paddle wheel mode stirrer and "finger stock" pressure seal. (Courtesy Varian Associates)

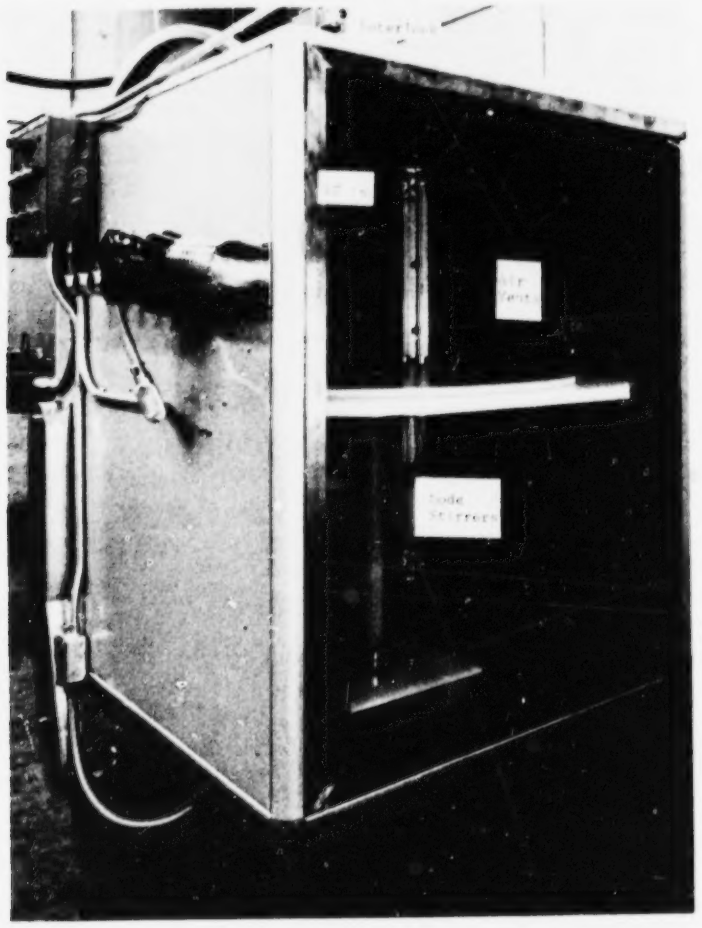


Figure 15. Batch oven showing mode stirrers, RF entrance port, air vents, blower, door interlock, and "finger stock" door seal. (Courtesy Varian Associates)

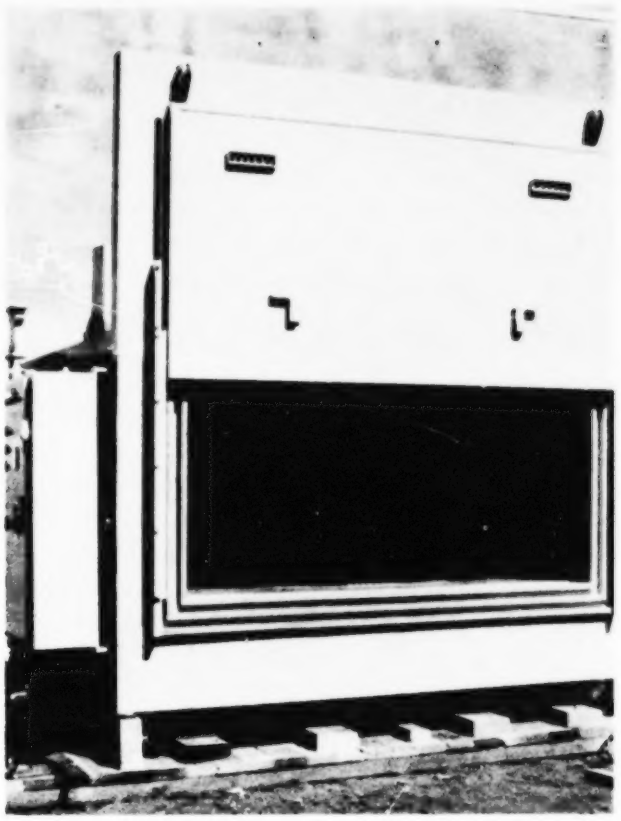


Figure 16. Industrial batch oven showing double quarter-wave choke seal and waveguide-beyond-cutoff viewing windows. (Courtesy Varian Associates)

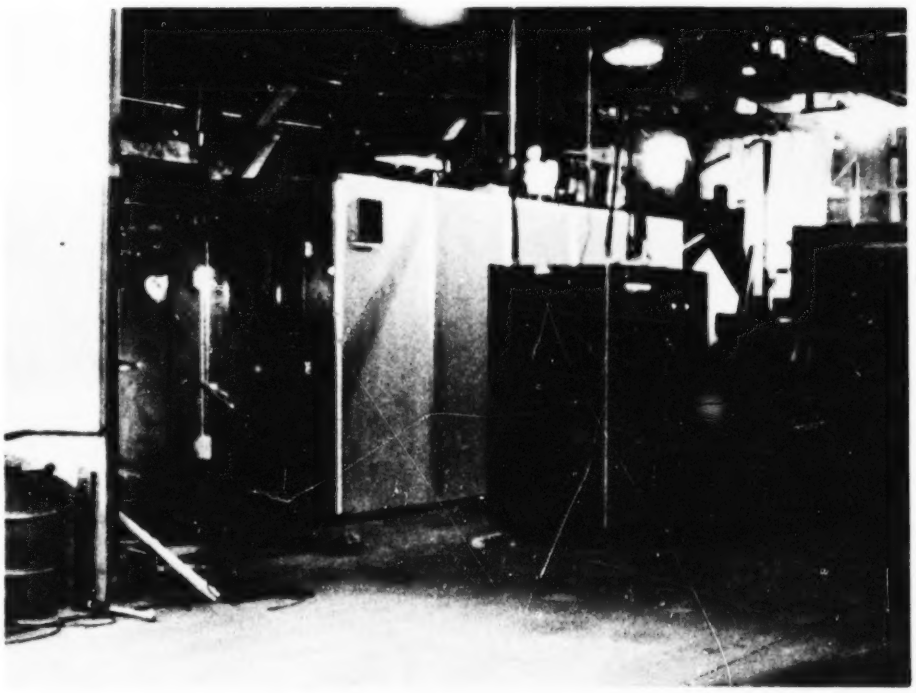


Figure 17. Large kiln used to cure tanoak for baseball bats. (Courtesy Varian Associates)

satisfactory. Leakage remained less than 1 mW/cm^2 with two fingers missing and did not exceed 3 mW/cm^2 until four adjacent fingers, the number at which the manufacturer of the unit recommends replacement of the finger stock, were removed. Figure 14 also shows an interlock on the outside wall, again for safety. A factory survey of three leading industrial microwave manufacturers[1] revealed that all equipment examined (batch, semiautomatic, and conveyorized) had at least one interlock on all doors which could be opened during operation.

Figure 15 shows another batch oven with paddle-wheel mode stirrers and a finger stock metal pressure door seal. Also shown are the waveguide port through which energy enters the cavity, forced-air fan, circular air vents made up of waveguide-beyond-cutoff to prevent leakage, and the door interlock at the top left.

Figures 16 and 17 are examples of larger industrial batch ovens. The unit in figure 16 uses a double quarter-wave choke seal to prevent door leakage as well as a vertically sliding door to avoid possibly troublesome door hinges. The two viewing screens within the door are made up of rectangular waveguide-beyond-cutoff, and the control panel is safely located on the side of the oven. Finally, the unit in figure 17 is a large kiln used to cure tanoak for "Oregon Slammer" baseball bats, shown with its power pack and connecting waveguide sections.

2.3.3.2 Semiautomatic Units

A typical automated batch unit is shown in figure 18. The major points of interest here are the entrance and exit ports which are hydraulically operated. When the doors are closed, a tight metal-to-metal seal is maintained by hydraulically compressing the entrance door between the two metal frames, eliminating the possibility of accidental door opening during operation. The demand for this type of unit has been much less than that for the fully conveyorized unit.

2.3.3.3 Fully Conveyorized Units

Of major importance in designing a fully conveyorized industrial microwave system is the prevention of leakage from the conveyor ports and easy access to the resonant cavity for quick cleaning.

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[1] Cryodry Corporation, Genesys Systems, and Varian Associates.

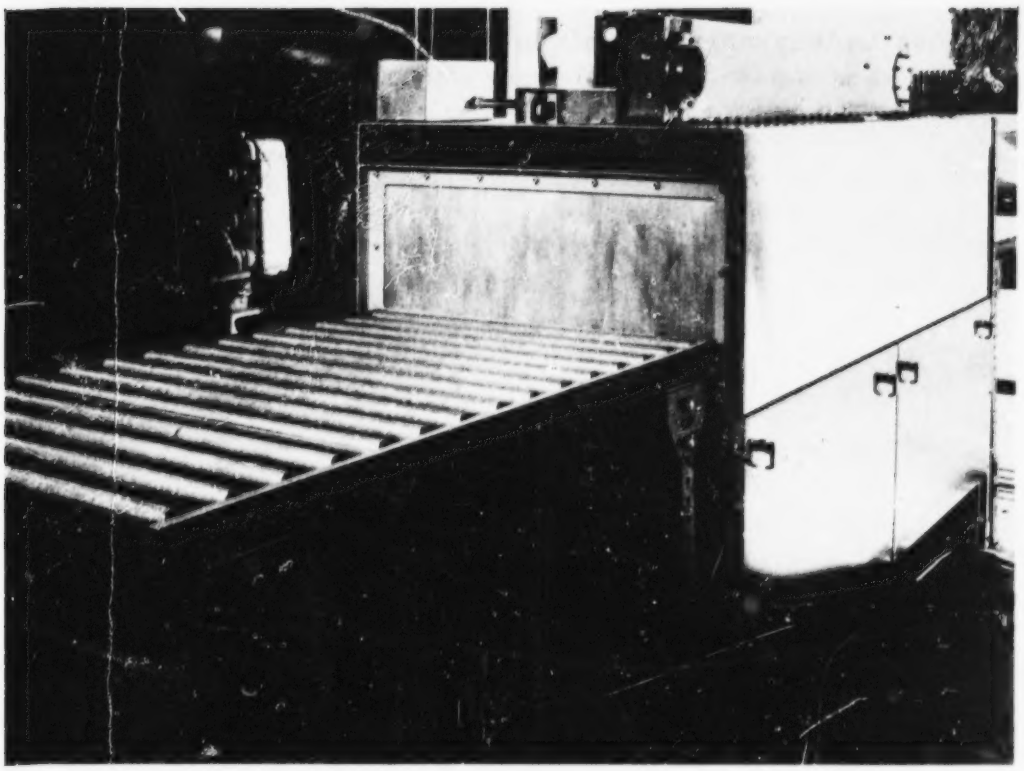

Figure 18. Semiautomatic batch processor.
(Courtesy Genesys Systems)

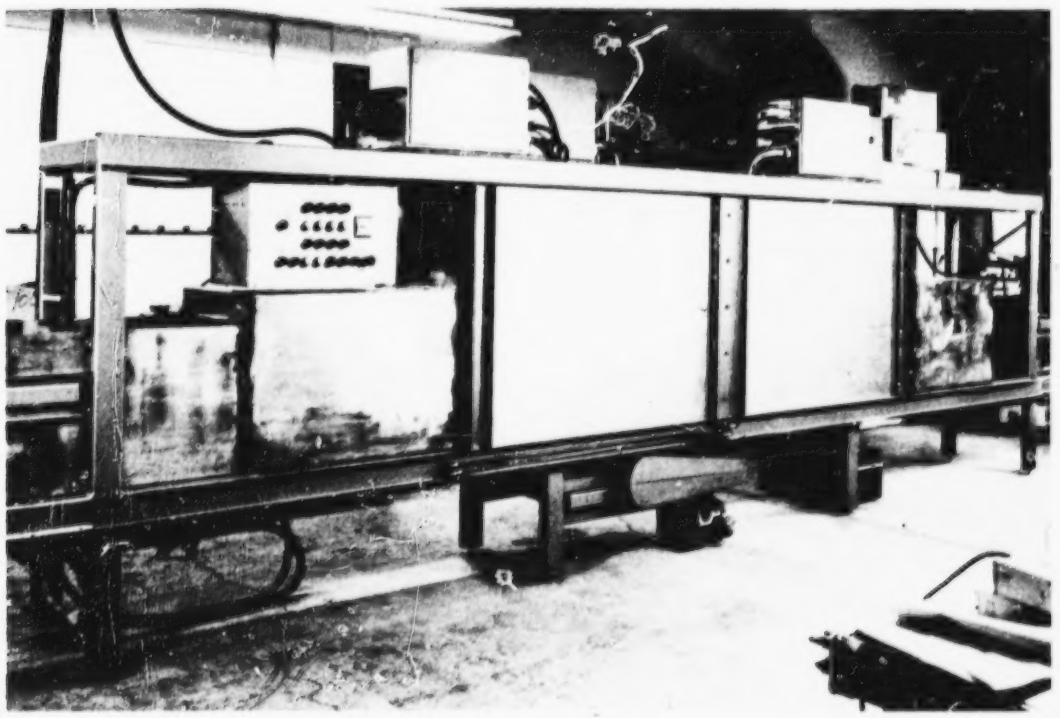

Figure 19. Fully conveyorized microwave system for cooking and/or drying. (Courtesy Genesys Systems)

The most widely used technique to minimize leakage from the conveyor openings is to surround the conveyor with water pipes as it enters and leaves the resonant chamber. Figure 19 shows a fairly representative conveyorized system including the cavity area, water load chambers, water pipes, control panel, power pack, and cavity doors. The water loads themselves consume as much, if not more, space than the resonant cavity. Not shown in the photograph is that the water flow rate is monitored to ensure that the circulation is adequate to keep the water from boiling. The system shuts down automatically if this condition is not met. The control panel has warning lights to inform the operator when the generating tubes are on, off, or on standby; there is also a provision for running the belt in either direction. The access doors for cleaning have metal-to-metal pressure seals, with the pressure provided by water coils within the frame. When the doors are closed and the circulatory system started, the pressure from the tubing which surrounds the edges of both doors forces the doors against the frame and actually causes warping of the doors. Opening of these doors during operation is thus made impossible.

Figure 20 shows a typical water load. The water pipes, separated from the resonant cavity by a small slot, surround the conveyor and fill the outer chamber to reduce leakage from the conveyor exit to less than 10 mW/cm^2, the maximum leakage design figure used by manufacturers questioned.[1]

Figure 21 shows a slightly older system with an extensive resonant cavity. Ubiquitous waveguide applicators are positioned to achieve as uniform a field pattern as possible. The cleaning doors again have the metal-to-metal pressure seal with the pressure coming from large bolts to prevent accidental opening. Should such an opening occur during operation, however, each door is equipped with an interlock to shut the system down.

Figure 22 shows a closeup of the slot size of a conveyor opening, as well as four air ducts consisting of waveguide-beyond-cutoff, and a rectangular waveguide applicator for introducing RF energy into the cavity.

Finally, figure 23 shows still another cleaning door design. A double choke door seal is used on a vertically sliding door; the pipes extending from the doors are waveguide-beyond-cutoff viewing windows.

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[1] Cryodry Corporation, Genesys Systems, Raytheon Company, and Varian Associates.

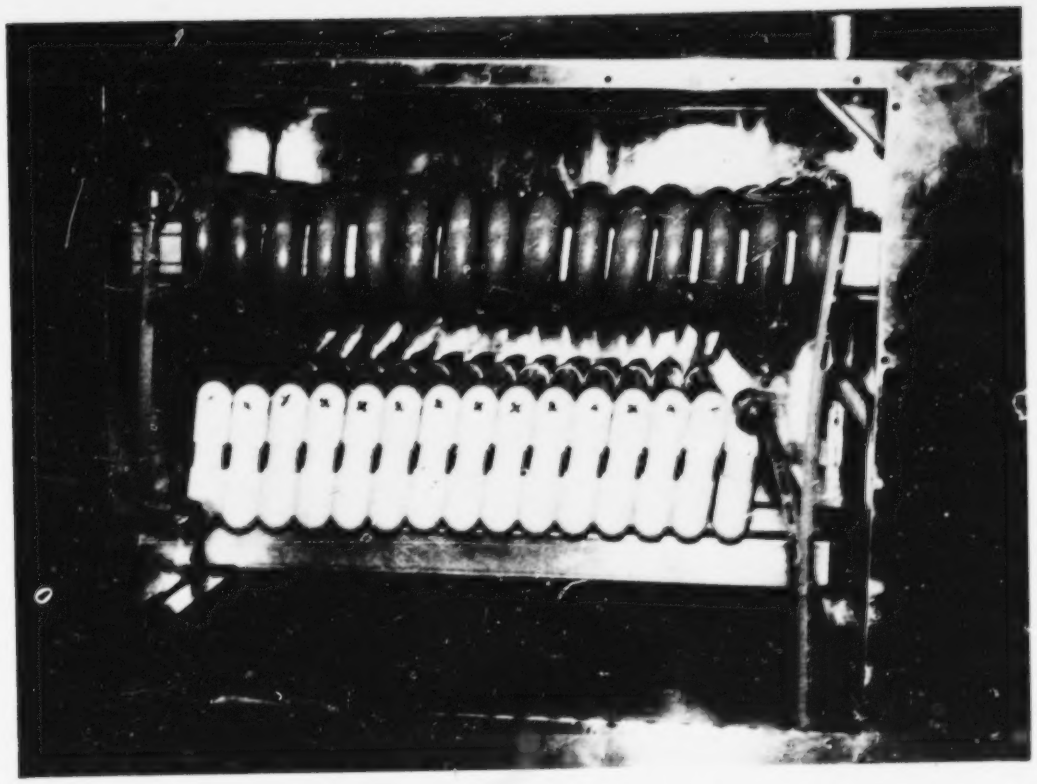

Figure 20. Typical water load assembly from a fully conveyorized unit. (Courtesy Cryodry Corporation)

Figure 21. Fully conveyorized multimode cavity showing side door interlocks, dissipating load, and RF applicators. (Courtesy Varian Associates)

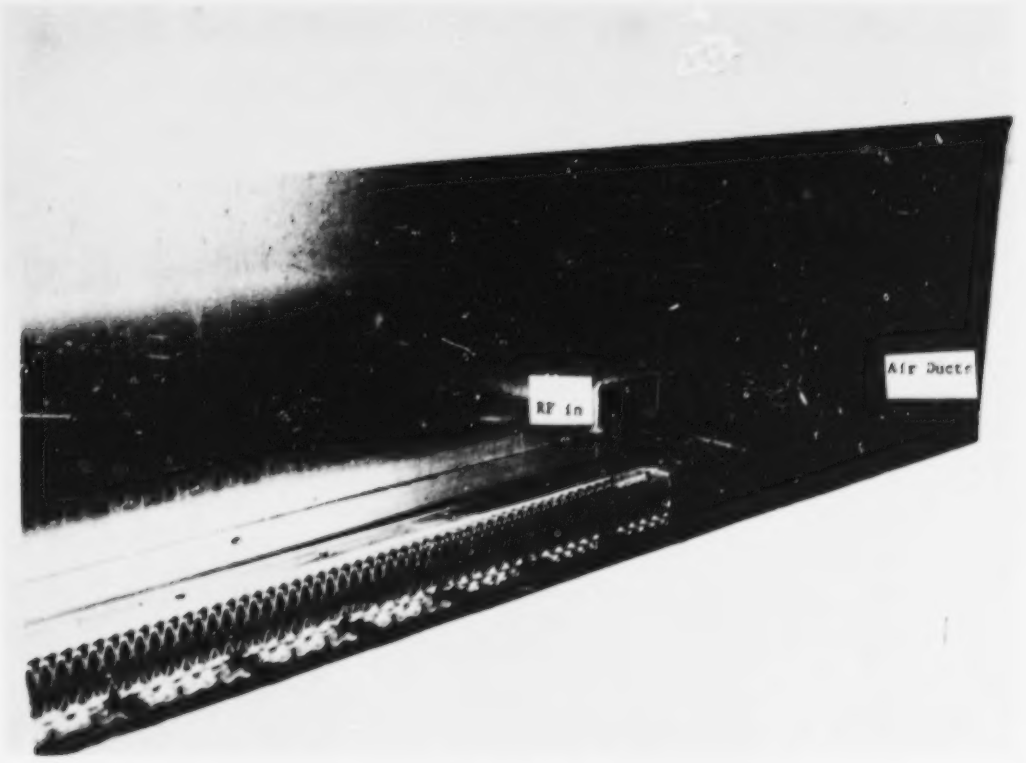

Figure 22. View of RF input, air vents, and conveyor opening in a fully conveyorized multimode cavity assembly. (Courtesy Varian Associates)

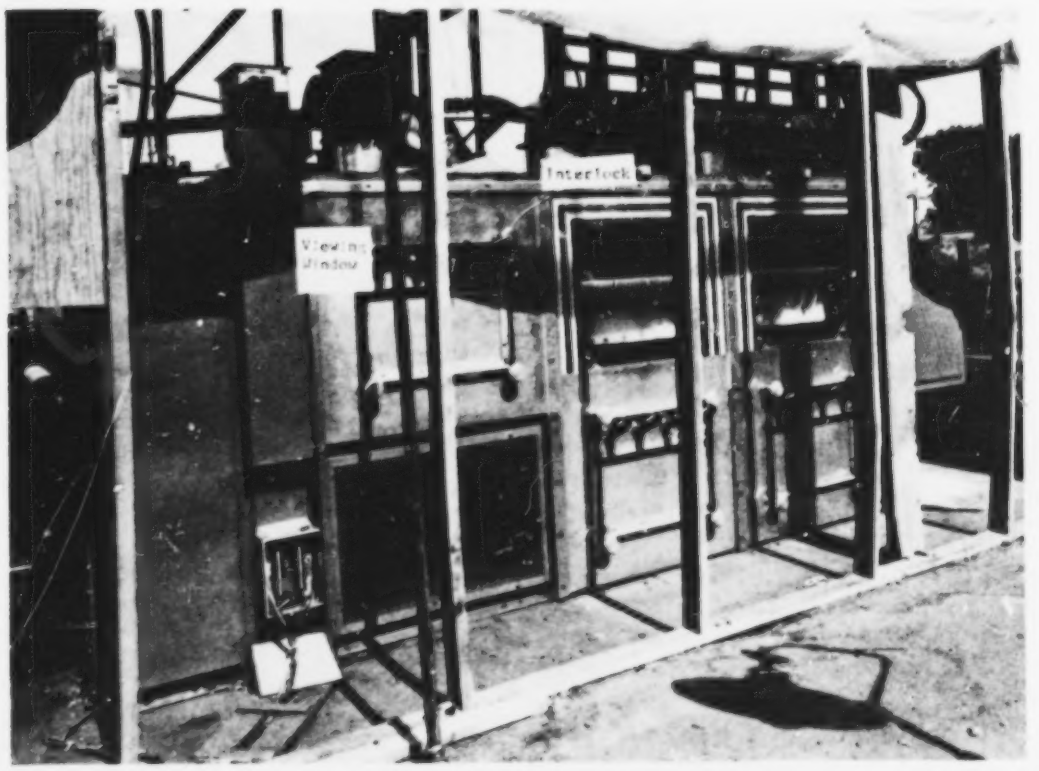

Figure 23. Industrial unit showing waveguide-beyond-cutoff viewing ports, double choke door seals, interlocks, and vertically sliding doors. (Courtesy Varian Associates)

2.3.4 Fringing Field Applicator

The preceding sections have emphasized some of the basic features of batch, semiautomatic, and fully conveyorized multimode cavity systems. The final applicator considered is the fringing field applicator, shown in figure 24. Like the meandering waveguide and conveyorized cavity units, it is best suited to thin materials. As in the folded waveguide of figure 8, the RF energy travels back and forth across the applicator, gradually giving up energy to the material passing beneath it. A typical heating pattern from the applicator is shown in figure 25 where the dark areas represent the most intense heating. Uniform overall heating is achieved because of the even distribution of both hot and cold spots. The holes shown in the applicator housing (fig. 24) enable forced air drying to take place simultaneously with the microwave processing. No leakage occurs through these holes since their diameter is less than a quarter wavelength. Figure 26 shows a conveyor-eye view of the applicator and gives a better idea of the slot thickness. An example of a possible drying system using this applicator was shown in figure 4, where two applicators were lined up lengthwise. The system shown was simple and effective, yet considerably less expensive and less bulky than conventional dryers.

To minimize leakage from the conveyor slots, a combination of water loading and absorbing material is used. Figures 26 through 29 show an applicator set up for both forced air and microwave drying. The large amount of water loading and absorbing material shown in figures 26 and 27 is required so that leakage will not exceed safe levels even when no material is being processed. Figure 28 shows the waveguide-to-coax termination through which the RF is introduced and the safety interlock which shuts the system down if the applicator is disassembled during operation. Figure 29 shows the assembled system, pointing out the slot width and air vents.

2.4 SAFETY FEATURES

In the design of most pieces of equipment described in the preceding sections, numerous safety features were included as "standard" equipment. Among those mentioned were the following: water pressure door seals, double quarter-wave choke seal, finger stock metal pressure seals, rugged door construction and lack of troublesome hinges, water load circulation monitoring, interlocks on all doors, bolted doors on large conveyorized units, and control panel of monitoring lights.

Not mentioned in the discussion of fully conveyorized units was the presence of arc detectors. It is possible that a metal object or grease accumulation could cause potentially harmful arcing with a resultant fire hazard while a product is being conveyed through the resonant cavity. For this reason, arc detectors are placed in the cavity. Should arcing occur, the detector automatically shuts down the system until the problem has been corrected.

A major factor in the safety of any industrial machine is a safe operating procedure. During a visit to the plant of one manufacturer of industrial microwave equipment, several machines were observed in operation. At no time did anyone attempt to activate the power tubes without first checking all warning lights, nor did anyone attempt to open a cleaning door without first checking to make certain the power was off. In one attempt to start up a machine, the water circulation monitor warned of inadequate circulation, and the flow was promptly adjusted before applying the RF.

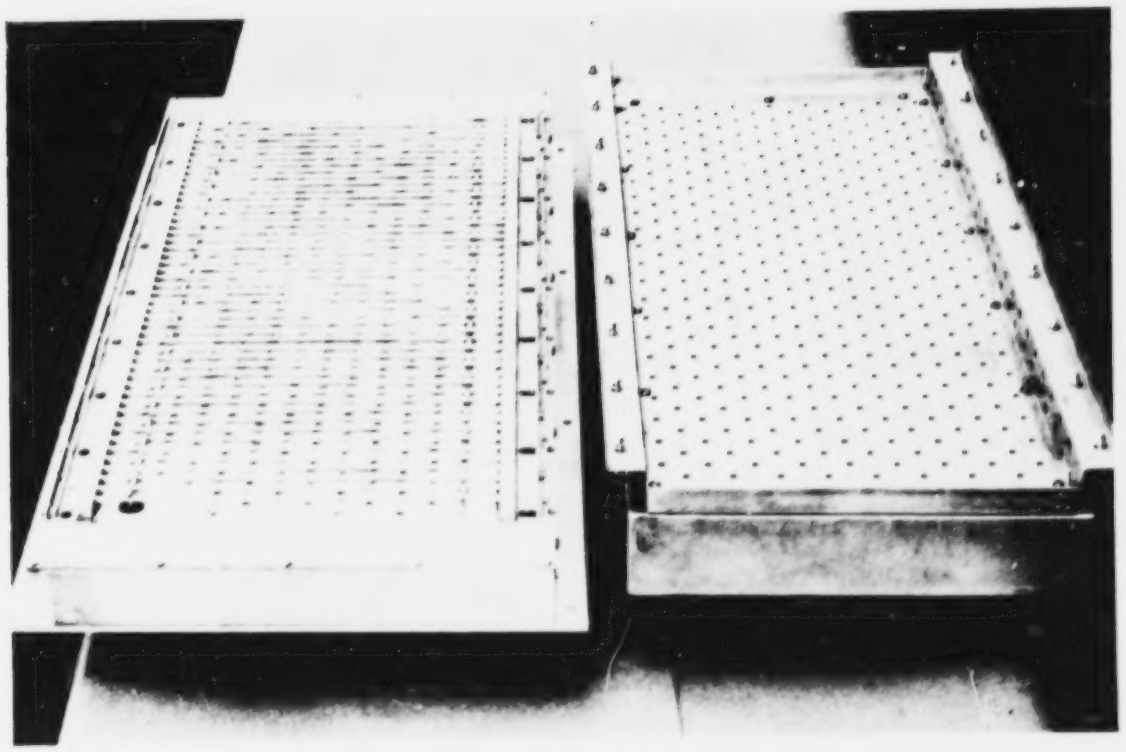

Figure 24. Fringing field applicator.
(Courtesy Genesys Systems)

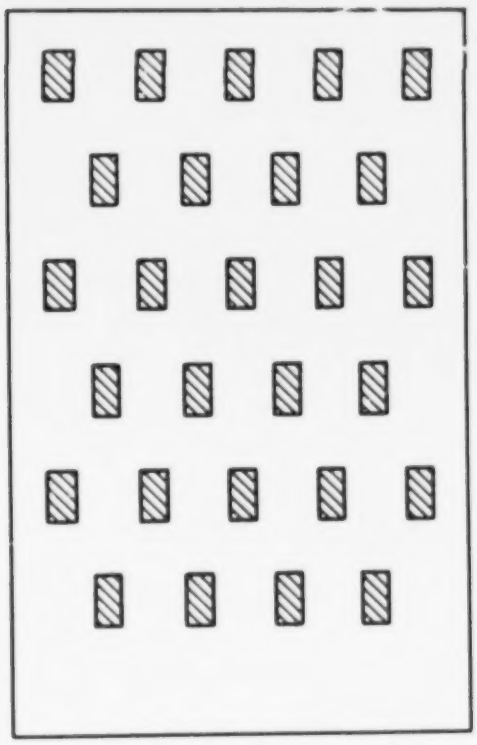

Figure 25. Schematic heating pattern of fringing field applicator showing even distribution of energy.

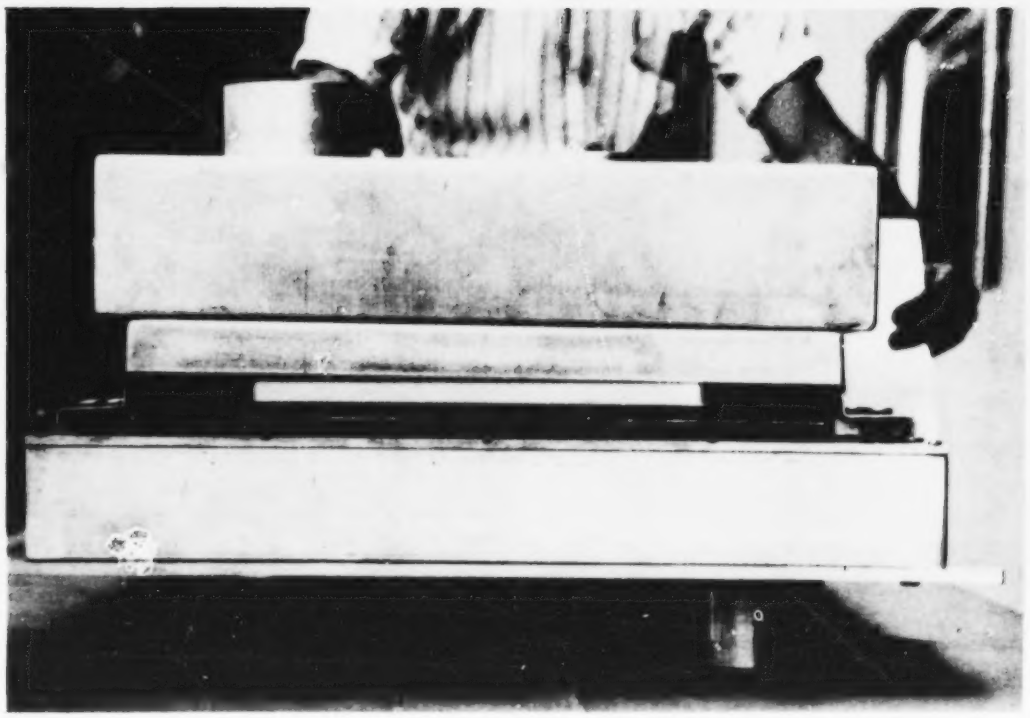

Figure 26. Conveyor-eye view of applicator and slot width. (Courtesy Genesys Systems)

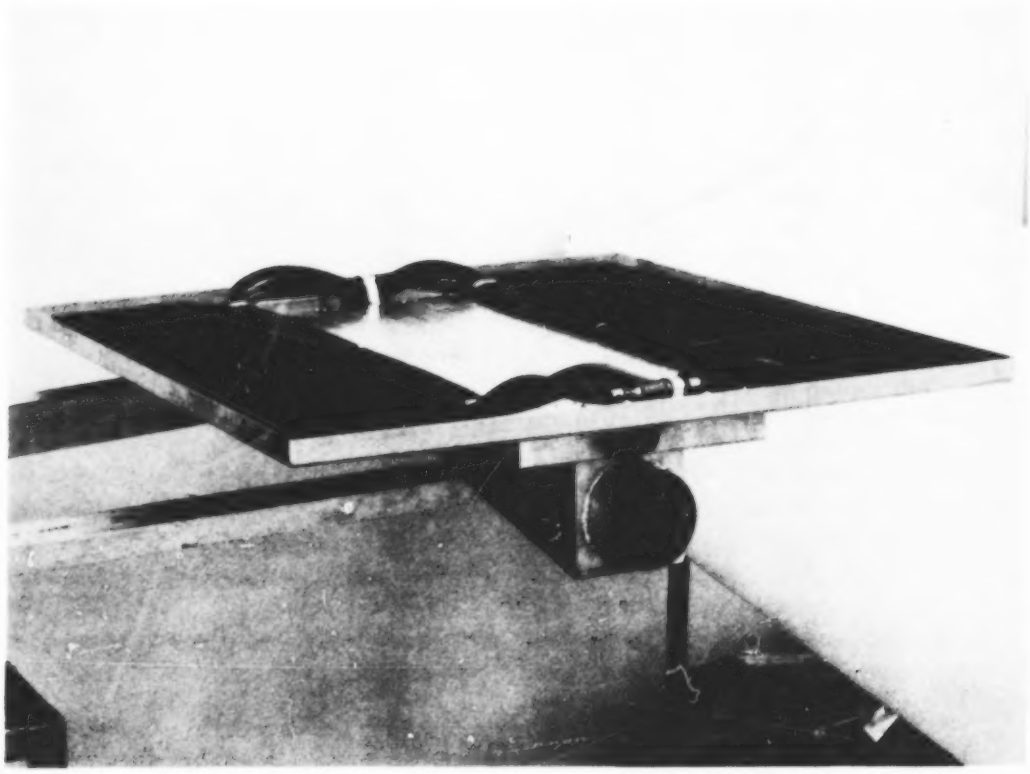

Figure 27. Applicator top with water loading and absorptive material to minimize leakage. (Courtesy Genesys Systems)

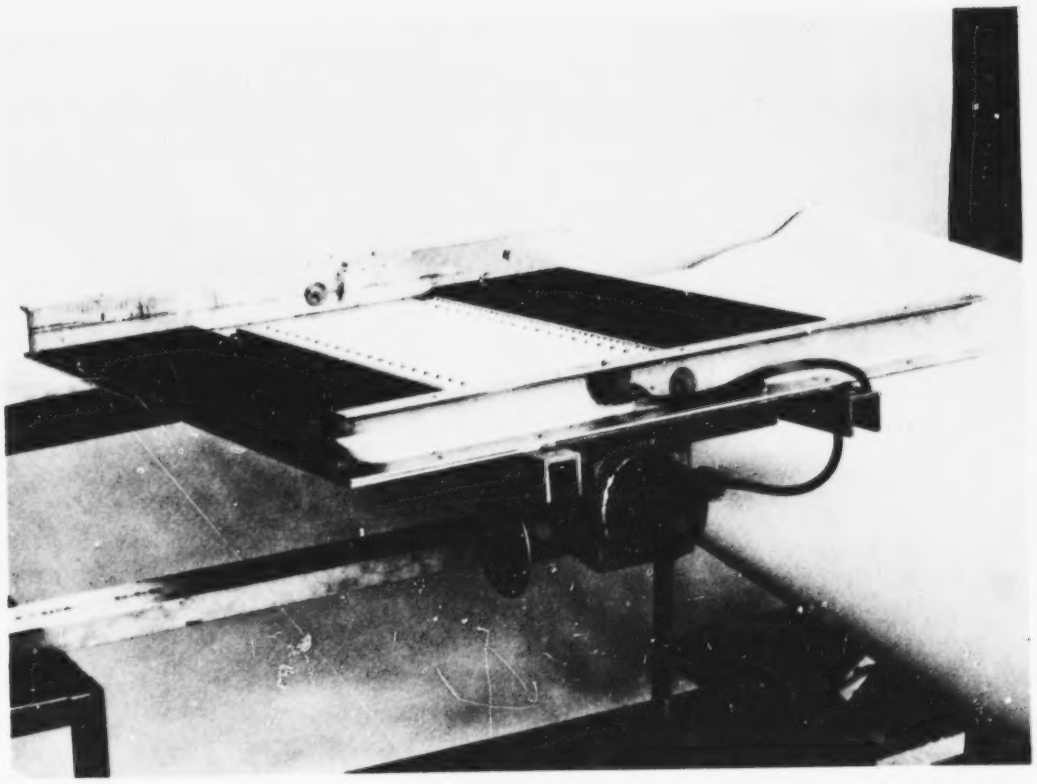

Figure 28. Applicator bottom showing interlock and absorptive material. (Courtesy Genesys Systems)

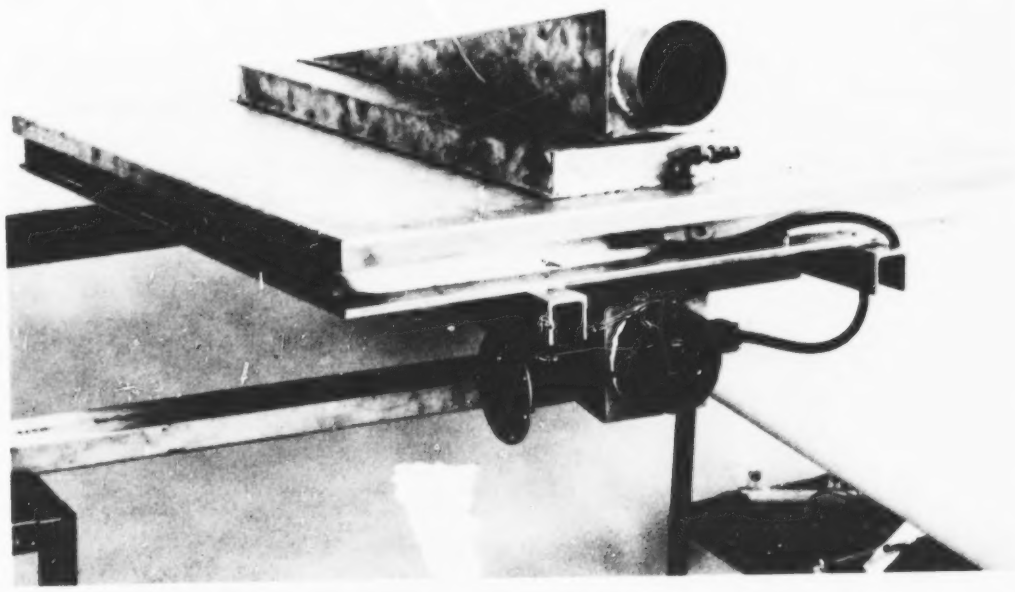

Figure 29. Assembled system showing air vents and conveyor slot width. (Courtesy Genesys Systems)

3. INDUSTRIAL APPLICATIONS OF MICROWAVES

This section presents a survey of several of the most established industrial applications of microwave energy. Because of the competitive nature of the industry, many applications still in the R&D stage could not be included in this report. Nonetheless, numerous microwave systems have been developed for many different industries, of which the following are several:

Food Industry

Final drying of potato chips
Poultry processing
Bacon precooking
Freeze drying
Thawing of frozen food
Donut cooking

Forest Products Industry

Hardwood drying
Veneer drying
Paper drying
Newsprint drying

Plastics Industry

Sealing of plastics

Mining Industry

Curing of concrete
Breaking of concrete

Chemical Industry

High-temperature chemical processing
Curing epoxy resin impregnated pipe

Materials Field

Destruction of dry rot fungus in wood and brick
Destruction of woodworm in timber

Other

Pharmaceuticals
Leather drying
Grain drying
Film drying
Match head drying

3.1 MICROWAVE DRYING

Figure 30 is a graph of the drying cycle for a typical substance in air; it is a plot of the moisture content of the material versus time, and is an exponentially decaying function.

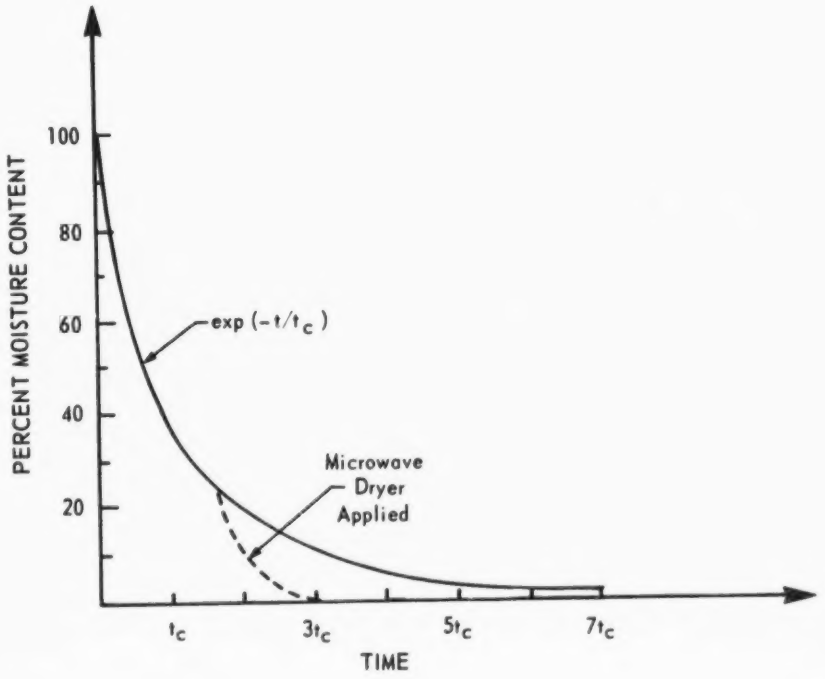

Figure 30. Drying cycle for a typical substance in air.

The time constant, t_c, is similar to the skin depth outlined in appendix A in that it represents the time it takes the function to

decay to 1/e (36.8 percent) of its value at any instant. In terms of drying, this means that the material will initially dry very rapidly because of its large moisture content, but considerably more time will be required to remove the final 10 to 20 percent of its moisture. Microwave drying is used to speed up this final moisture removal. The rapid internal heating drives moisture to the surface where it quickly evaporates, thereby increasing the overall drying speed. In most industrial drying applications it is uneconomical to completely dry a product with microwave energy because conventional air drying is much less expensive and almost as efficient for initially high moisture levels. Most systems have therefore relied on a combination of the two methods, using conventional drying at the outset and microwave drying to remove the final 10 to 20 percent of the moisture.

3.2 FOOD INDUSTRY

The food industry was the first area to receive considerable attention from microwave processing when Cryodry Corporation completed a machine to finish-dry potato chips in 1962. Since that time the industry has continued to receive a great deal of attention because of the growing use of microwave ovens in homes and the increased demand for precooked foods.

3.2.1 Finish Drying of Potato Chips

A good potato chip is one which is golden yellow in color and has a crisp but not brittle texture (moisture content of about 2 percent). O'Meara (5), Wade (4), and others have pointed out that the presence of sugars, primarily glucose, in potatoes has the undesirable effect of browning the chips during the final stages of the deep fat frying process when the chips' moisture content is in the 5 to 10 percent range. This browning results in an overly high percentage of marginal or totally unsalable chips.

Microwave finish drying is able to prevent this unwanted browning and waste. The chips are removed from the deep fat fryer when their moisture content is about 10 percent and conveyed through a microwave dryer until the desired 2 percent moisture level is reached. Because of the internal heating of microwaves, the surrounding exterior temperatures remain relatively cool, and browning is avoided. Figure 31 shows a typical finish dryer with the chips entering the microwave dryer at the upper right end of the unit and exiting from the lower left. The process is fully automatic and requires no supervision during operation.

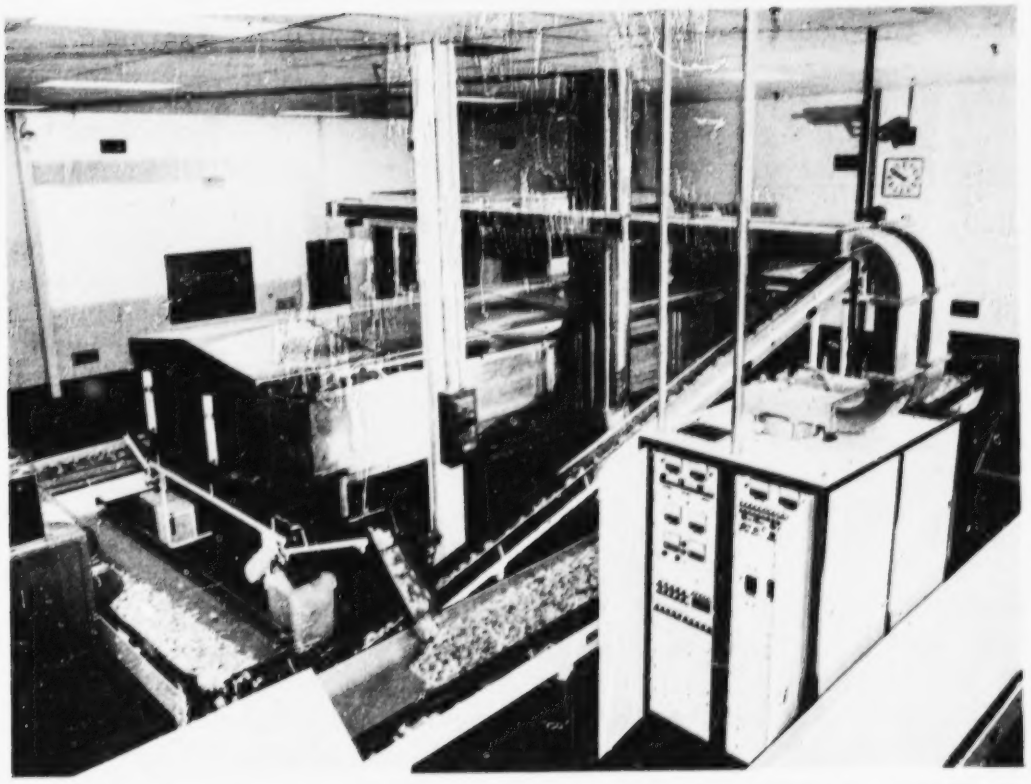

Figure 31. A 50-kW 915-MHz continuous system for finish drying potato chips. (Courtesy Cryodry Corporation)

Microwave processing also alleviates the potato storage problem. The lower the temperature at which potatoes can be stored, the longer will be their mean time before spoilage. With conventional processing, potatoes must be stored at temperatures near 50°F since their sugar content increases at temperatures below this level and unwanted browning occurs during the final steps of processing. Microwave drying permits the potatoes to be stored at a lower temperature of 40° to 45°F (5) because they need only to be deep fried in fat until browning starts to occur, at which time they are transferred to the microwave finish dryer and dried to the desired final moisture content without further browning.

A typical 50-kW system, such as that shown in figure 31, can process up to 2,000 pounds per hour of finished chips, depending on the moisture content of the chips. O'Meara (5) and Wade (4) have estimated the operating costs for such a system at $5.50 per hour (this figure includes utilities, tube amortization, and cleanup labor) and amortization of the microwave unit at $12.50 per hour (assuming only one-shift operation). The total system operating cost

is then $18.00 per hour, or about one cent per pound of finished chips.

3.2.2 Poultry Processing

Microwave processing has also proven feasible in the precooking of chicken parts and other poultry. Previous precooking techniques, steam or hot water, require about one hour to heat the chicken throughout to the desired temperature of 185°F (4). This lengthy cooking time often results in dried-out chicken and unwanted bone darkening. Because of its good penetration depth and internal heating, however, microwave processing is able to achieve the same internal temperatures in less than five minutes, preventing unnecessary drying out and bone darkening. In addition, the yield of usable chicken increases from 85 percent to as high as 88 to 90 percent.

An economic analysis of three systems of precooking chicken has been made by May (7). The three systems are batch steam, conveyorized steam, and conveyorized microwave in a steam atmosphere. Batch steam systems have been the most widely used of the three, but they require up to 10 extra laborers to supervise and maintain the process. The conveyorized-steam and microwave-steam systems do not have this disadvantage and result in savings of up to $30 per hour in labor alone.

May's results, tabulated in tables 3, 4, and 5, are based on a throughput of 2,500 pounds of chicken per hour. Table 3 compares the direct operating costs of the three systems and shows that the conveyorized systems offer up to 25 percent savings over the less efficient batch unit in this area, based on a two-shift operation. Table 4 compares the three systems over a one-year period on a cost per pound basis (still assuming a constant throughput of 2,500 pounds per hour). The two conveyorized systems both offer direct cost savings of $120,000 per year, but the microwave steam system has an additional savings of $180,000 per year because of the higher yield achievable with microwave processing. The net result is a savings of 1.2 cents per pound for conveyorized steam and 3.0 cents per pound for conventional microwave cooking. Table 5 next compares the capital investment required for cooking, conveying, and chilling for the three production systems and the final return on investment for each system. Although the initial cost of the microwave system is substantially greater than that of either steam system, the reduced labor expenditures and improved yield enable the conveyorized microwave system to offer the highest return on investment (64 percent).

Table 3. Economic analysis of direct operating costs in three chicken cooking systems (2500 lb/hr) (7)

Cost item	Steam batch	Steam conveyor	Microwave conveyor[a]
Labor (at $2.00/hr)	$74.00(37 hr)	$54.00(27 hr)	$54.00(27 hr)
Manufacturing overhead	37.00	27.00	27.00
Total labor and overhead/hr	$111.00	$81.00	$81.00
Electricity ($0.01/kWh)			
Cooking	-	-	$1.80
Freezing	$6.00	$6.00	6.00
Miscellaneous	1.00	1.00	1.00
Steam	4.00	4.00	2.00
Water	3.00	3.00	2.00
Total utility cost/hr	$14.00	$14.00	$12.80
Maintenance	3.00	3.00	2.50
Tube replacement cost	-	-	1.80
Total direct costs/hr	$128.00	$98.00	$98.10
Total direct costs/shift	$1,024.00	$784.00	$784.80
Total direct costs/ 2 shifts	$2,048.00	$1,568.00	$1,569.60

[a]Microwave system uses a steam atmosphere at about 190-200°F.

Table 4. Economic analysis of conveyorized steam and microwave cooking advantages over batch steam for cooking chicken (2500 lb/hr) (7)

Cost item	Steam batch	Steam conveyor	Microwave conveyor
Total direct costs/day[a]	$ 2,048	$ 1,568	$ 1,570
Product input (lb/day)	40,000	40,000	40,000
Direct cost/lb	0.0512	0.0392	0.0392
Direct cost savings/lb		0.0120	0.0120
Direct cost savings (10 million)		120,000	120,000
Yield improvement/yr (3% at $0.60/lb)		-	180,000
Operating advantage/yr		$120,000	$300,000
Savings/lb		1.2¢	3.0¢

[a]From table 3.

Table 5. Capital investment and return to investment of three cooking systems[a] (7)

	Steam batch	Steam conveyor	Microwave conveyor
Tanks, racks, and trays	$8,500	-	-
Cookers	24,000	$125,000	$230,000
Transfer conveyors	-	10,000	10,000
Chiller	8,000	18,500	18,500
	$40,500	$113,000	$218,000
Added investment over batch system		$113,000	$218,000
Operating advantage/yr (BT)		120,000[b]	300,000[b]
Operating advantage/yr (AT)		60,000	150,000
Depreciation, 5-year straight line(AT)		11,300	21,800
Net cash flow (AT)		71,300	171,800
Payout (yr)		1.56	1.27
Return on investment		51%	64%

[a]Figures for batch steam are composite values based on actual production costs from industrial systems. Those for conveyorized microwave in a steam atmosphere are based on pilot plant data and projected costs. Conveyorized steam figures are believed to be realistic projections.

Items of equipment common to all three systems are not shown. Such items would include cut-up lines, breading machines, fryers, and packaging equipment.

[b]Does not include a floor space advantage of approximately 4000-5000 sq. ft. over batch steam.

3.2.3 Bacon Precooking

Several manufacturers are presently developing a system for precooking bacon, but as yet little information has been reported on completed systems. One of the problems with bacon is that it cooks best when it cooks slowly, so a unit must be designed which does not instantly overcook and spoil the bacon.

3.2.4 Freeze Drying

Freeze drying is a relatively recent food preservation technique in which microwave energy can play a significant role. Parker (8) has pointed out that in conventional freeze-drying processes, the frozen material being dried is placed in a vacuum chamber where a regulated amount of heat is applied through liquid-cooled trays. The freeze drying occurs when the temperature and pressure within the chamber are adjusted so that the ice within the frozen material sublimes but the material remains frozen. A typical operating temperature and pressure would be 0°C and 1 Torr (1 mm of Hg). After the water vapor has been drawn off, the dried food can be hermetically sealed for storage or shipment without refrigeration. By merely adding water, the product once again becomes suitable for eating or cooking. In addition to longer shelf life without refrigeration, freeze drying has the benefit of preserving vitamins, proteins, and original flavor better than other preservation methods.

The problem with freeze drying which microwave processing can alleviate is that conventional drying often takes from 8 to 24 hours to completely sublime the ice. Experiments with microwave drying (8) have shown comparable results after only one to two hours of drying. Such savings enable up to 10 times more material to be freeze dried from a given unit than was previously possible.

In analyzing the costs of freeze drying, Parker (8) states that "Economic studies.... for large microwave freeze-drying plants predict operating costs of 3 to 4 cents per pound of water removed. Current conventional freeze-drying costs vary from two to five times this much. Furthermore, the capital investment required to fully facilitate a production-sized plant for microwave freeze-drying is approximately 30% less than for a conventional plant of equivalent product output."

Freeze drying therefore represents another process for which the internal heating and quality control of microwave energy offer several advantages over conventional heating techniques.

3.2.5 Thawing of Frozen Foods

Although little information is available on installations using microwave thawing techniques, microwave energy offers a quick, uniform way to thaw frozen materials. Using conventional techniques, a frozen block could require from 4 to 24 hours to thaw, depending on size and method of thawing. Decareau (9) mentions that most thawing in food plants is accomplished by removing the material from the freezer and letting it sit at room temperature for a day or so. This technique is quite unsatisfactory because after a lengthy time interval the outside surface could be thawed, dried out, and unusable before the center has thawed. The good penetration depth and internal heating of microwave energy could very satisfactorily be used to thaw a block of frozen material in one-tenth the time of ambient thawing with far less spoilage due to excessive dryness, color change, or bacterial growth on the surface. Microwave thawing equipment is expensive, however, and food manufacturers for the moment appear content to use conventional thawing techniques rather than risk the large expenditure on new equipment.

3.2.6 Donut Cooking

Donut cooking is another area in which considerable research and development work is now being undertaken to perfect a microwave processing system. Little information is available from the manufacturers at present, but it is conjectured that, as with potato chips, the microwave system's chief function will be to finish-dry the donuts as they come out of the deep fat fryer to reduce spoilage.

3.3 FOREST PRODUCTS INDUSTRY

Voss and Supplee (10) have stated that the two greatest needs of the expanding forest products industries are faster curing and drying speeds and greater quality control. Microwave processing can help solve both these needs.

Conventional wood drying techniques require large kilns, high humidity, and high ambient temperatures to heat the wood. The drying time is limited by the rate at which moisture can be brought to the surface of the wood and by the rate at which it evaporates from the surface. The high humidity of the kiln makes surface evaporation quite slow, however, and the poor thermal conductivity of wood results in very slow heating of the interior of the wood. The net result is a very slow, difficult to control drying system which produces inferior quality wood. Unfortunately, at the other extreme,

if drying occurs too rapidly, then structural damage can occur over large surface areas. Studies (10) have shown that microwave drying can achieve the desired quality control, speed, and uniformity required to satisfactorily meet the demands of the industry. Four areas in which microwave drying has been successfully applied are (1) rapid seasoning of hardwood, (2) veneer drying, (3) moisture leveling in paper, and (4) rapid newsprint drying.

3.3.1 Hardwood Drying

Hardwood drying must be well controlled to prevent defects from forming within the wood. Conventional air and kiln methods are both lengthy and difficult to control. They can require from two weeks to two years to dry the wood depending on the condition of the lumber, can often give spotty results, and can entail enormous inventories. Microwave processing eliminates these defects. Most woods fortunately have self-limiting drying properties; that is, the drier they become, the less RF energy they absorb.

An added feature of microwave curing and drying is that it is well suited for woods which, because of varying or unusually large moisture contents, are unsuitable for conventional kiln processing. An example of this is "tanoak," a little-known and formerly little-used hardwood from the Pacific Northwest. As described in the April 1969 Varian Associates Magazine (11), it has an "extreme hardness matched in its uncured state only by its moistness." Conventional kiln drying required over 60 days and gave unreliable results. Microwave drying, however, such as that shown in figure 32 at Tanoak Industries where potential "Oregon Slammer" baseball bats are being cured and dried, requires only a four-hour initial curing time and a final five-day finish drying to achieve the desired moisture levels. Test results indicate that the microwave-processed bats are more durable and longer hitting than conventional ash bats.

3.3.2 Veneer Drying

Veneer drying is another application in which the self-leveling characteristics and speed of microwave drying are advantageous. Conventional hot air drying of veneer is slow and uncontrollable, resulting in costly, inefficient drying and substantial material loss. Microwave drying eliminates these drawbacks. Using a meandering waveguide applicator (fig. 33), the veneer dries uniformly to the desired moisture content, and unwanted "hot spots" or overdried sections are avoided.

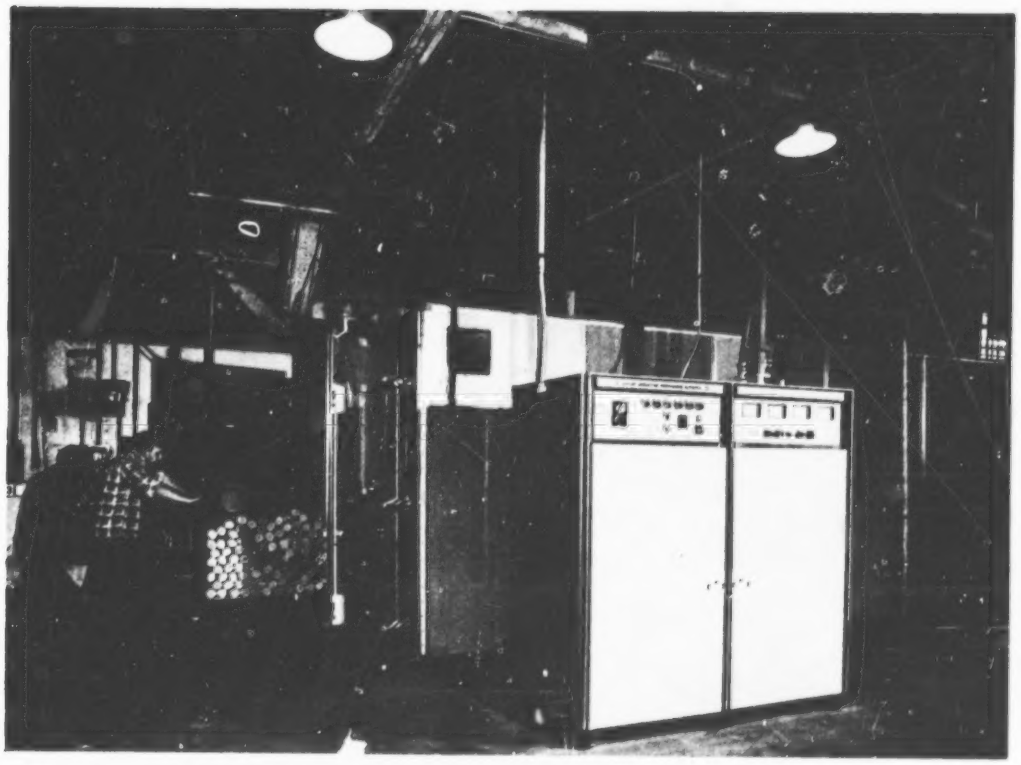

Figure 32. Kiln for curing tanoak at Tanoak Industries. (Courtesy Varian Associates)

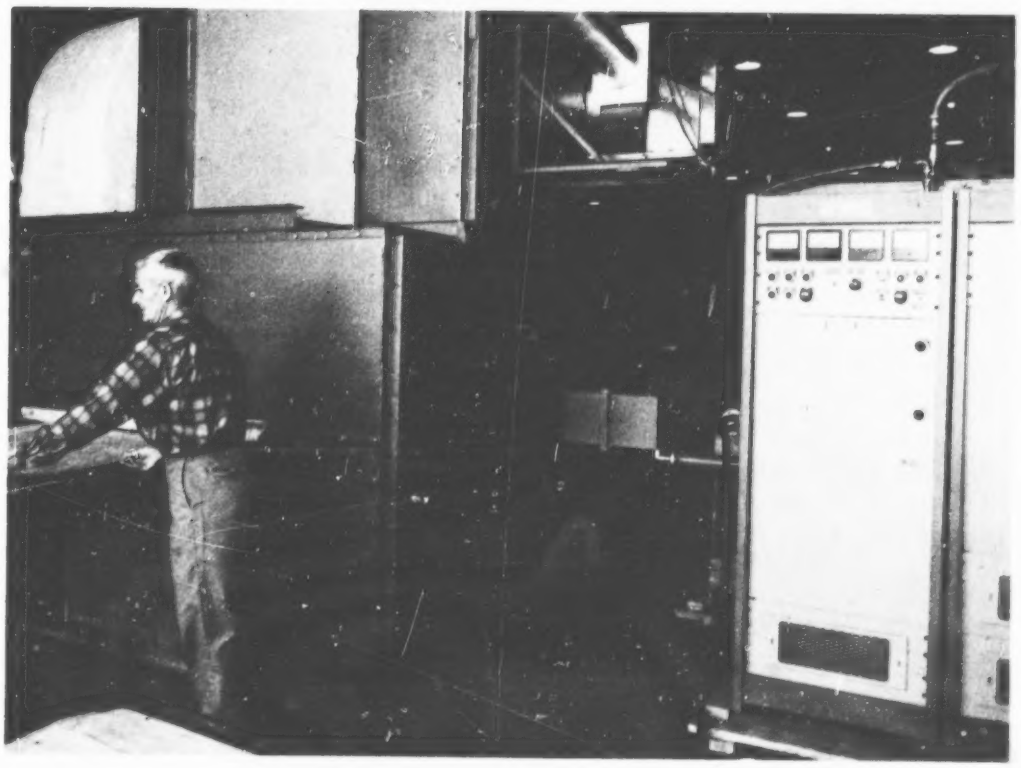

Figure 33. Veneer drying. (Courtesy Varian Associates)

3.3.3 Moisture Leveling in Paper

The main advantage of using microwaves for moisture leveling in paper is the self-regulating dielectric properties of the paper being processed; the wettest areas absorb the most power, resulting in a gradual leveling of the moisture content with time.

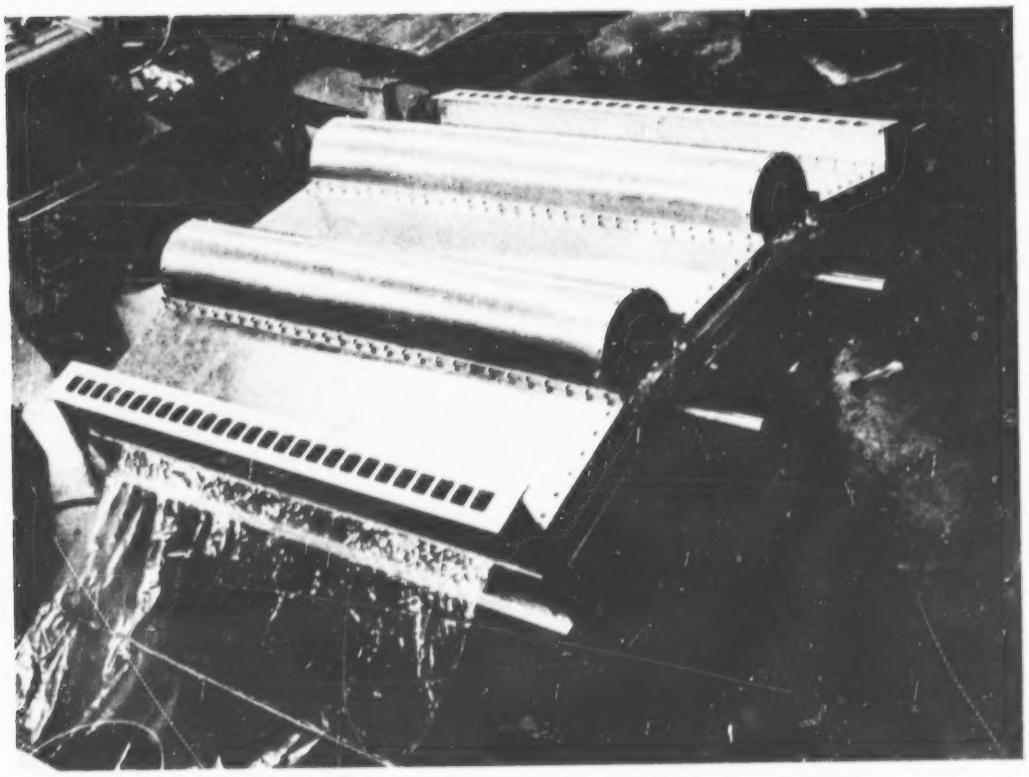

Figure 34. Applicator suitable for drying thin films such as paper. (Courtesy Varian Associates)

Goerz and Jolly (12) have analyzed the economic advantages of microwave drying over conventional hot air drying in the paper industry. Their findings point out the more uniform moisture profile resulting from microwave drying as well as savings in floor space and a 25-percent reduction in cost per pound of water removed.

3.3.4 Ink Drying

The rapid drying capabilities of microwave processing have been applied to the newspaper industry and show considerable promise, especially in the area of color photographs where conventional absorption drying is too slow to give good results at the necessary high-speed production rates. A major problem in this area has been the development of inks which respond quickly to microwave heating. The formulation of such inks has been described by Gerling (13). The advantages of microwave drying over conventional absorption drying are discussed in detail by Moore (14) and include the following: complete drying at lower conveyor temperatures; improved product quality; more uniform moisture content in the paper; easy access to drying unit; instant control of heating; environs cooler than with hot air drying; no need for extensive high-temperature insulation; no vapors to remove; lower paper costs; lower chill roller costs; and finally lower operating costs.

3.4 PLASTICS INDUSTRY

The application of microwaves to the sealing of plastics makes use of the rapid, concentrated, internal heating microwave energy can achieve. White (15) points out that the best seals occur when the heating rate is so fast that negligible heat flow occurs in the time to bring the interface to the fusion temperature, which is why the rapid heating of microwaves is so useful. No other heating method is sufficiently fast or concentrated to form a comparable seal.

The example cited by White as a specific case of plastic sealing with microwave energy involves Du Pont Tedlar, a polyvinyl fluoride film which transmits all frequencies of sunlight and is not degraded by the sun's radiation. Hence, it is well suited for greenhouses and other solar energy uses. The microwave sealing unit is shown in figure 35. It differs from the units discussed thus far in that it is low power (200 W) and is neither conveyorized nor batch but "portable", making it suitable for repair work in the field. The completed structure, shown in figure 36, is made up of a series of narrow strips of Tedlar sealed together.

A major benefit of microwave seals of this type is that they preserve the desirable features of the Tedlar, notably its transparency to all components of sunlight and its strength. The tensile strength of the seam shown was actually greater than the elastic limit of the Tedlar itself. In addition, it proved very durable, giving years of leak-proof service.

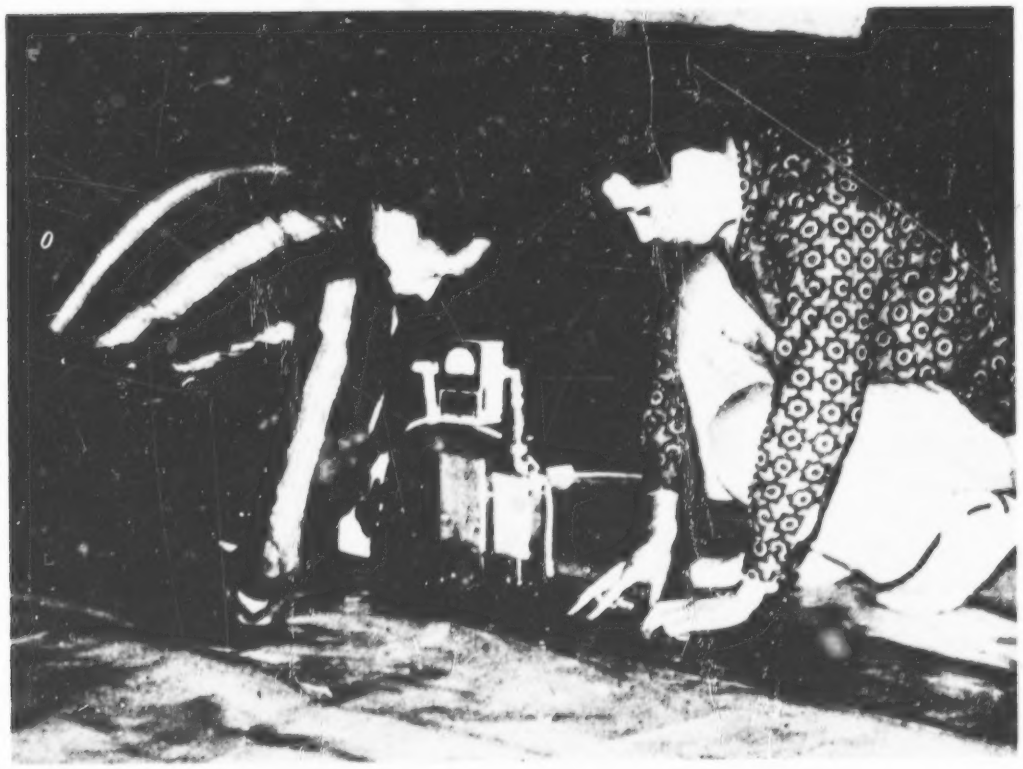

Figure 35. Microwave sealing of Tedlar.
(Courtesy Varian Associates)

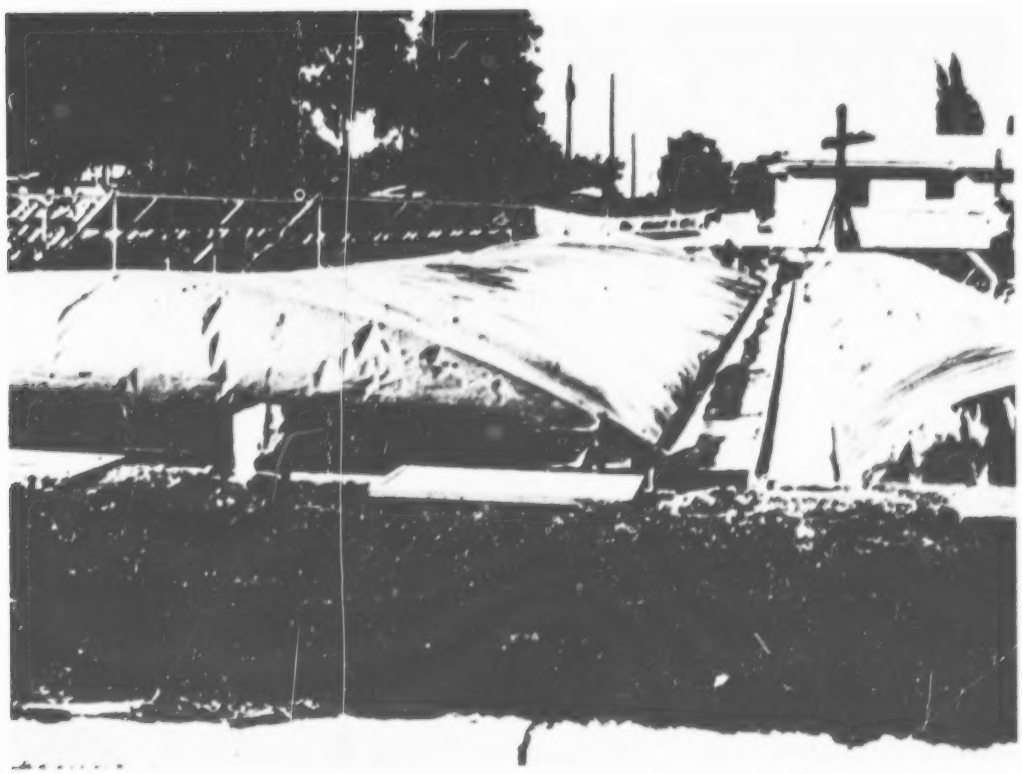

Figure 36. Installation of microwave-seamed Tedlar film.
(Courtesy Varian Associates)

3.5 MINING INDUSTRY

Applications of microwave energy to the mining industry have centered primarily around work with concrete. Two applications will be discussed: the curing of concrete with microwaves and the use of microwave energy to demolish hardened concrete.

3.5.1 Curing of Concrete

In conventional curing of concrete, the finished material is allowed to sit at ambient temperatures for up to 28 days to achieve its full strength. This lengthy time period can be reduced to a period of four hours by steam curing, but a loss in the final strength of the concrete accompanies the process. Watson (16) has reported on experiments with batch microwave ovens at 2450 MHz to speed up the curing process. These tests point out that although the microwave-cured concrete initially had greater compressive strength than a normally-cured sample, the normal curing process produced considerably stronger concrete after a 28-day period. Watson (16) has suggested that further tests be conducted at increased pressure and lower frequency to try to correct the problem.

3.5.2 Breaking of Concrete

The breaking of aged concrete is another example of the R&D work being attempted with microwave power. Watson (17) has reported the use of a modified log-horn antenna with a narrow strip aperture to generate intense local heating in a thin area of concrete. This intense local heating forces the heated concrete to expand, creating large tensile stresses in adjacent areas and resulting in cracking of the concrete. In the experiment described, a concrete slab five feet square and nine inches thick was cracked across the middle in six minutes with a 5-kW source. While pointing out the feasibility of using microwaves to break concrete, Watson indicates that the tests still leave major problems -- notably, how to separate the cracked portions, especially if the concrete is reinforced.

3.6 CHEMICAL INDUSTRY

Microwave energy has found several applications in the chemical industry for both curing and heating. Figure 37 shows the world's largest microwave processing system installed in a major automobile manufacturing plant to rapidly cure polyurethane for automobile seats. Two other applications, outlined below, are high-temperature chemical heating and epoxy resin pipe curing, both of which rely on the selective internal heating offered by microwaves.

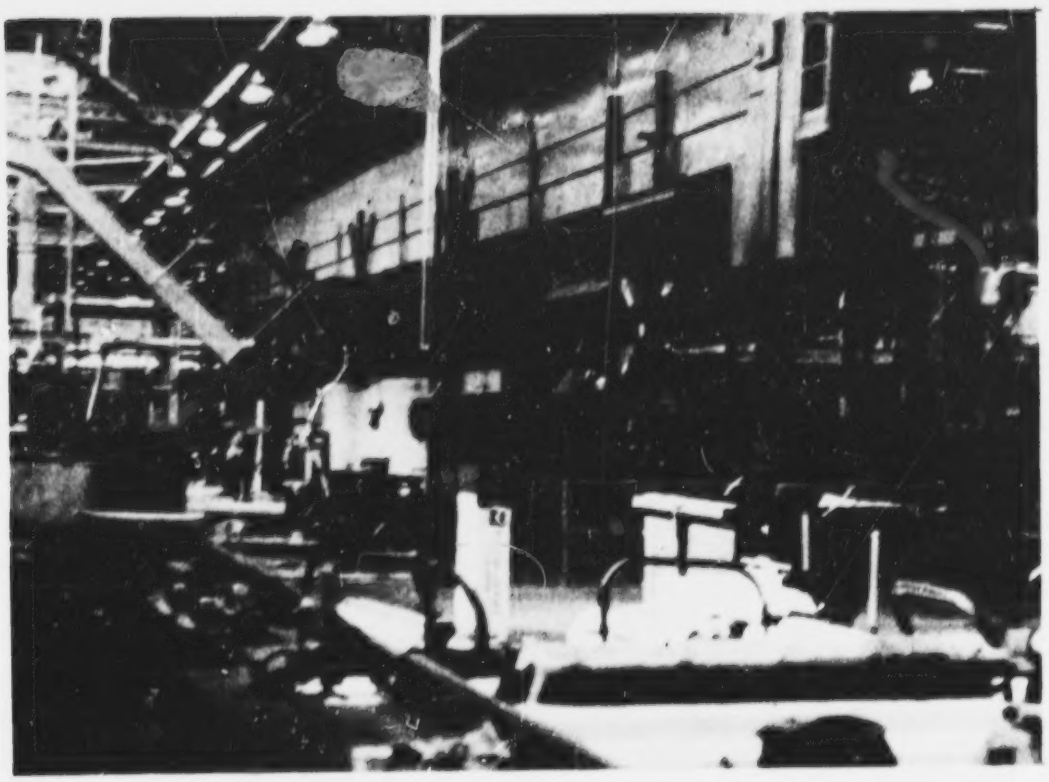

Figure 37. Urethane curing at a major U.S. auto plant.
(Courtesy Varian Associates)

3.6.1 High-Temperature Chemical Processing

Ford and Pei (18) have described experiments in which microwave batch ovens operating at 2450 MHz have been used to heat various classes of solid compounds to temperatures in excess of 1000°C. The advantages of microwave heating are its ability to heat the desired material to high temperatures while keeping the surroundings relatively cool and the rapidity with which it can achieve this heating.

Figures 38 and 39 show microwave heating being used to transform aluminum silicate pellets into a solid abrasive. The cylindrical container in figure 38 is made of copper tubing through which cold water is circulated during operation to keep the outer layer of pellets from melting. The entire assembly is located in a laboratory batch oven such as that shown in figure 15. When the power is applied, the energy absorbed within the aluminum silicate pellets quickly becomes sufficient to melt the pellets everywhere except in the thin outer shell which is kept cool by the circulating water. As the power is reduced, the molten aluminum silicate hardens and leaves a rugged abrasive block such as that shown in figure 39. Because no conventional heating methods are able to selectively heat the interior of an object without also scorching the surroundings, the above example represents an application for which microwave processing is the only known method of achieving the desired result, although the technique is presently limited to research work.

3.6.2 Curing Epoxy Resin Impregnated Pipe

Another microwave drying application which shows considerable promise is the curing of glass fiber-reinforced epoxy tubing (19). The apparatus shown in figure 40 was used to cure the resin impregnated tubing. The pipe itself is continuously produced by winding glass fiber strands over a pipe mold, impregnating it with epoxy resin, and then curing until a solid, durable tube results. The resin has the desired self-regulating property which produces even hardening of the pipe without hot spots. Production rates of 20 inches per minute have been achieved with a 20-kW 2450-MHz microwave system, but this rate was limited more by the winding of the glass fiber tube than by the microwave curing. Examples of finished tubing are shown in figure 41.

A major advantage of epoxy-glass fiber tubing is that it is very strong, very durable, and impervious to corrosion. Similar techniques have been used to manufacture nose cones for missiles out of the same materials. Epoxy-glass fiber pipes have also been mentioned as possible components for the trans-Alaskan pipeline now under consideration for transporting oil from the Prudhoe oil fields to northern California.

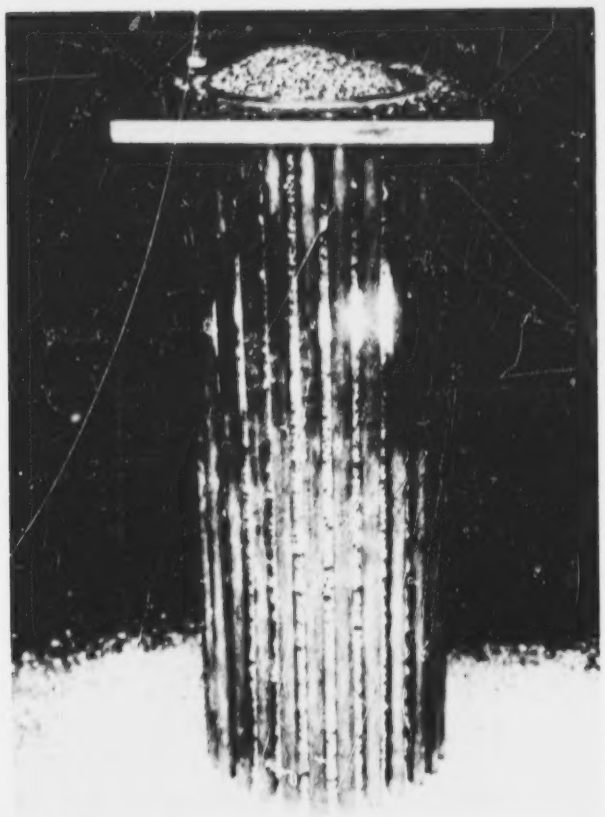

Figure 38. Container for aluminum silicate pellets inside a laboratory batch oven. (Courtesy Varian Associates)

Figure 39. Processed abrasive. (Courtesy Varian Associates)

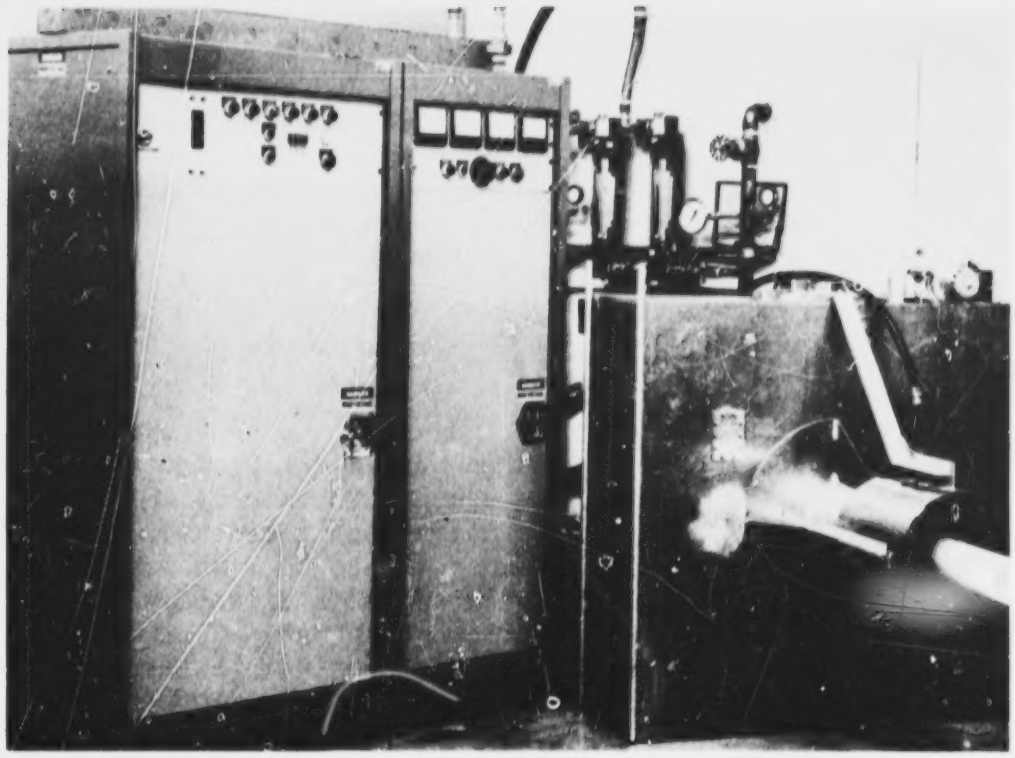

Figure 40. Applicator system for curing epoxy resin impregnated pipe. (Courtesy Varian Associates)

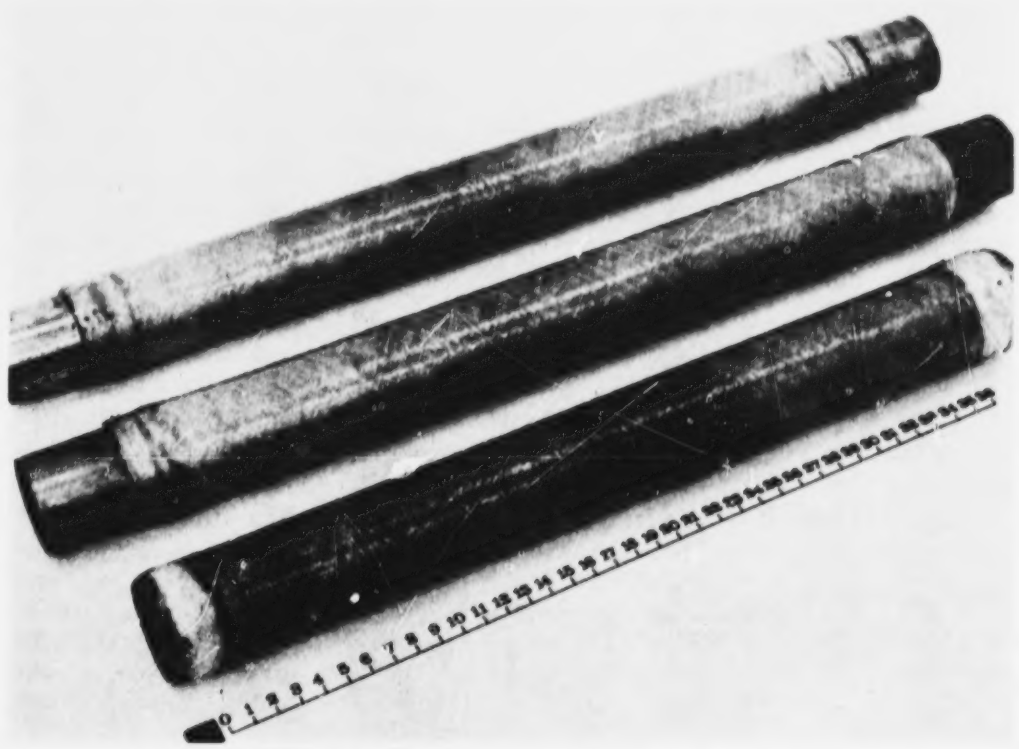

Figure 41. Processed pipe. (Courtesy Varian Associates)

3.7 FUNGUS CONTROL

The use of microwave heating to destroy fungus in brick and woodworm in timber has been partially successful. Because of its deep penetration and internal heating, microwave energy is able to quickly heat the unwanted fungus or woodworm above a critical temperature for as long as is necessary to destroy it.

3.7.1 Destruction of Dry Rot Fungus

Watson (20) reports that dry rot fungus can be destroyed by raising its temperature above 40°C for a period of 10 minutes. Conventional thermal heating techniques require excessively long periods of time to achieve the desired 40°C temperature in brick or timber for all but the thinnest of walls because of the poor thermal conductivity of these materials. For thick walls it is entirely unsatisfactory. Watson reports that a 2-kW microwave heating system operating at 2450 MHz can destroy dry rot fungus in a 9-inch-thick brick wall with only 20 minutes of heating.

The treatment of fungus in wood was not as successful because during development the fungus irreversibly weakened the wood. Thus, although the microwaves were able to destroy the fungus, the wood itself was still too weak for use. The established technique of sawing off the ends of the affected areas two or three feet into the unaffected wood still appears to be the best way to handle the fungus problem.

3.7.2 Destruction of Woodworm in Timber

The conventional method of destroying woodworm in timber is to spread a liquid pesticide over the surface or, if the timber is thick, to inject the pesticide into the holes made by the woodworm. Internal heating again offers a more direct solution, especially for thick pieces of timber. Watson (21) reports that temperatures of 65°C are necessary to destroy the woodworm but that these temperatures need be sustained for only a few minutes. Experiments show that the method is effective in destroying woodworm, but considerable effort will be required to perfect an effective, safe system for disinfecting an entire building because of radiation reflections from screening within the building and nails in walls and also because of the possible fire hazard from the heating of the walls themselves.

3.8 MATCH HEAD DRYING

Another promising application is the use of microwave energy to dry match heads. Initial investigations by Genesys Systems and Fosforera Venezolana[1] have shown that microwave energy applied through a fringing field applicator can reduce the drying time of match heads from 20 minutes to less than 1 minute; a substantial saving in floor space can also result. Figures 42 and 43 show the present manner in which match heads are dried. Paper combs are conveyed through the match head solution and then meander up and down a drying rack for several hundred feet or more until dry. Figure 44 shows the experimental setup of the fringing field applicator at the start of the drying process. The off-axis orientation of the applicator shown in figure 44 did not turn out to be optimum, and vertical alignment produced faster drying. The results of these initial tests are summarized in tables 6 and 7; microwave case I is for the applicator as shown in figure 44, and case II is with the applicator vertically oriented. Genesys and Fosforera have agreed that initial results are favorable, and they are now undertaking further research to determine whether a different applicator orientation will permit still more rapid drying and/or whether hot air drying applied in conjunction with the microwave energy will dry the match heads more economically.

3.9 OTHER APPLICATIONS

Microwave processing has been applied to numerous other heating and drying applications where the deep penetration and quality control of microwave energy offer advantages over conventional drying and/or heating techniques. These applications include leather drying, grain drying, pharmaceutical drying, and film drying. In each case, rapid, uniform drying is obtainable with microwave energy in much the same manner as in previously discussed examples.

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[1] Information for this section was obtained from a trip report furnished by Mr. John Gerling of Genesys Systems. This report describes the pilot study installation of a match head dryer in the facilities of Fosforera Venezolana.

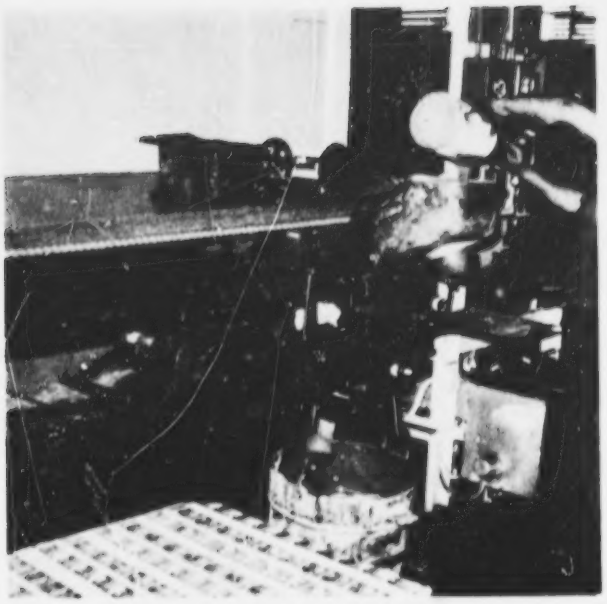

Figure 42. Conveyorized soaking of match heads. (Courtesy Genesys Systems and Fosforera Venezolana)

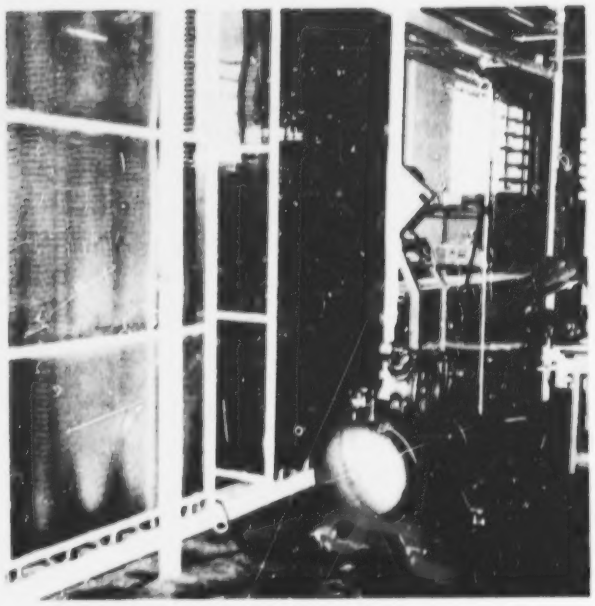

Figure 43. Conventional meandering drying rack. (Courtesy Genesys Systems and Fosforera Venezolana)

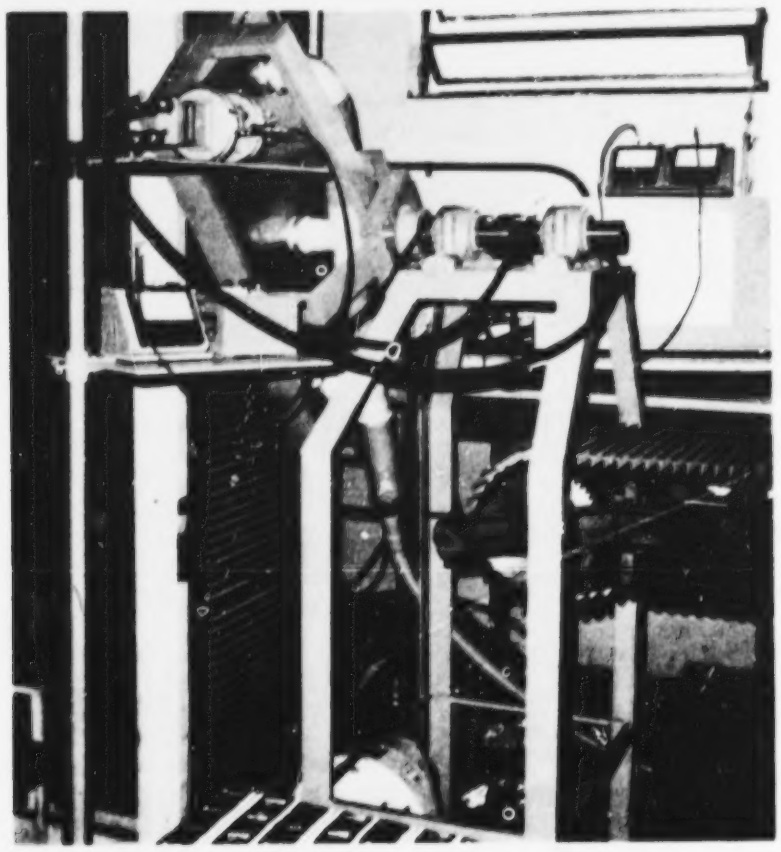

Figure 44. Experimental microwave dryer installed at start of drying rack. (Courtesy Genesys Systems and Fosforera Venezolana)

Table 6. Weight of water in match heads on a comb

	Water weight, normal process (grams)	Water weight, microwave case I (grams)	Water weight, microwave case II (grams)
Just applied	1.572	1.572	1.572
Just before microwave applicator	1.362	1.362	1.362
Just after microwave applicator	1.362	1.169	0.654
At take off	0.527		
Finished match	0.293		

Table 7. Book match machine data

1. Comb is 120 matches wide - 15 inches wide.
2. Combs are 1 inch apart on machine.
3. Comb without match head is 1-3/4 inches high.
4. Travel from application of match head material to microwave applicator = 38 feet.
5. Travel from application of match head material to comb take-off point = 495 feet.
6. Average machine speed during tests = 145 combs/minute.

4. EVALUATION AND CONCLUSIONS

4.1 RADIATION LEAKAGE LEVELS

In an earlier discussion of the safety features which microwave manufacturers build into their industrial equipment, one point that was mentioned but not emphasized was the radiation leakage levels to which the equipment is designed. Interviews with representatives from several manufacturers[1] have revealed that the industry, in cooperation with the International Microwave Power Institute (IMPI), has been using the power density figure of 10 mW/cm^2 as the maximum permissible radiation leakage level. All equipment has been designed to leak less than this amount during operation. Measurement of RF leakage from a 50-kW 915-MHz potato chip dryer such as that shown in figure 31 indicated maximum leakage of 12 mW/cm^2 just inside the conveyor exit port.[2] (Figure 31 shows that this area is inaccessible to personnel because of the conveyor belt assemblies.) The radiation leakage, when measured one foot from the opening, was below the 10-mW/cm^2 level. Radiation intensity at the entrance port was 3 mW/cm^2, and at the cleaning doors was everywhere less than 1 mW/cm^2. No attempt will be made to declare that measurements made on this single machine confirm uniformity throughout the industry, although the unit tested was in no way extraordinarily different from many other conveyorized assemblies. A more comprehensive survey would have to be made to acquire sufficient data to determine the leakage characteristics of an "average" machine.

4.2 EQUIPMENT RELIABILITY

A major problem plaguing commercial and domestic microwave ovens is mechanical wear and tear of the door and hinges which can result in unacceptably high radiation leakage levels after periods of use. Industrial systems minimize this drawback either by using a conveyor system or by using vertically sliding doors in batch ovens. In fully conveyorized equipment the major leakage hazard exists at the conveyor openings and is limited by the water loading. The water circulation is monitored, and the system will shut down if the flow is inadequate. Hence, there are no mechanically moving parts required to maintain the low leakage levels, and performance should not

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[1] Cryodry Corporation, Genesys Systems, Raytheon Company, and Varian Associates.

[2] Measurements were made with a Narda 8100 meter on a Cryodry 50-kW 915-MHz unit with the unit operating at half-power.

deteriorate with use. For large batch systems, where a door of some kind is required, hinged assemblies are often bypassed in favor of a more reliable vertically sliding door such as that shown in figure 16. Double choke seals reinforced with bolted assemblies to prevent accidental opening during operation, such as shown in figure 23, are far more rugged, long-lived, and tamper-proof than the door seals on low-powered domestic ovens.

No door failures or personal injuries resulting from equipment failure have been reported by customers to any of the microwave manufacturers visited for this investigation. One manufacturer's policy has been to assure clients, most of whom know little about microwaves, that their equipment will not leak in excess of the 10 mW/cm^2 design level during operation. A check is made during periodic maintenance inspection visits to verify that leakage is within these limits.

4.3 ESTIMATED NUMBER OF PERSONNEL EXPOSED

The number of industrial microwave systems in the U.S. has been estimated to be about 270 units, with the rate of production approximately five units per month.[1] Gerling[2] and others feel this figure is a bit high. Nevertheless, the number of people occupationally involved with the operation of this equipment can be estimated from this figure. It was pointed out that a major benefit of industrial microwave equipment is the small number of personnel required to supervise its operation. Figures 31 and 33 show zero and one operator respectively. Operation of an average unit should require no more than five attendants per shift. Based on a two-shift operation, that figure can be doubled to find the number of daily operators. By multiplying the number of personnel per machine by the number of machines, the total number of personnel involved throughout the industry can be estimated as less than 2,700. This figure is admittedly vague, but it is useful in estimating the number of people working near microwave equipment.

As for future developments, the number of units anticipated in operation by 1974 has been estimated to be between 600 and 800,[3] which implies that 6,000 to 8,000 operating personnel will be required at that time.

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[1]These numbers were taken from an unpublished report by J. Y. Harris, entitled "Revised Project Report for Electronic Product Inventory Survey," U.S. Public Health Service.

[2]Personal interview, January 7, 1970.

[3]From the same unpublished report by J. Y. Harris as given in footnote 1.

4.4 RECOMMENDATIONS

Because many industrial microwave units have output powers in excess of 25 kW, it is important that all safety features designed to prevent excessive leakage radiation function effectively throughout the life of the equipment. Therefore, it is recommended that the microwave manufacturers periodically examine their customers' installations annually or semiannually to ascertain the following information:

1) That radiation leakage from the entrance and exit ports of conveyorized units does not exceed the microwave radiation intensity levels[1] to which the equipment had been designed.

2) That radiation leakage from hinged and sliding doors does not exceed an intensity of 5 mW/cm^2 during operation, a feasible design figure as the previously cited leakage measurements at the cleaning doors of a 50-kW potato chip dryer pointed out. In cases where excessive leakage does occur because of worn door seals (for example, finger stock with several adjacent fingers missing), then these seals should be repaired or replaced.

3) That all interlocks and safety monitors are functioning correctly. For fully conveyorized units this examination should include all door and power pack interlocks, water circulation monitors, arc detectors, and the like.

4) That the tubing used in water loads is free from cracks and aging defects which could cause a sudden failure.

Few of the conveyorized units examined had caution notices at the conveyor entrance and exit ports warning personnel not to stick their fingers or other stray objects through the openings while the system is operating. Because the field intensity inside these openings can considerably exceed 10 mW/cm^2, such a warning should exist at both ports. If the material being processed were to snag inside the openings and no warnings were present, an operator unfamiliar with microwave radiation would be tempted to remove the snag without interrupting the RF power by sticking his hand through the conveyor slot, or worse by inserting a screwdriver or other metal object,

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[1] The instrument used to measure this leakage radiation should have a sensitivity comparable to that of the Narda 8100 Radiation Monitor.

with a resultant risk of injury. A warning such as

CAUTION MICROWAVES
DO NOT INSERT FINGERS
OR METAL OBJECTS
WHILE MACHINE OPERATING

placed at the conveyor opening could prevent such an accident.

Despite the interlocks on all doors, high powered systems are not designed to have these doors opened during operation. For this reason it is recommended that a caution notice also be placed on all doors reading something like the following:

CAUTION MICROWAVES
DO NOT OPEN DOOR
WHILE MACHINE OPERATING
EXCEPT IN EMERGENCY

Such a notice can reduce the possibility of accident by encouraging safe operating procedures.

Based on the preliminary examination of equipment at three manufacturers and the number of fully conveyorized industrial microwave systems, it is not recommended that the radiation leakage standard adopted for commercial and domestic microwave ovens[1] be extended to industrial units. High operating powers and conveyor openings make it unfeasible at the present time to construct a high-powered system with radiation leakage intensity less than 1 mW/cm^2. A more suitable approach for the time being would be to require the radiation from conveyor openings to be less than 10 mW/cm^2 and from other doors to be less than 5 mW/cm^2, both over the life of the system, with the manufacturer conducting periodic inspections to certify that the above leakage levels are not exceeded, as outlined above.

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[1]This standard requires that leakage radiation from an oven have an intensity less than 1 mW/cm^2 at the factory and no more than 5 mW/cm^2 over the life of the oven.

4.5 FUTURE DEVELOPMENTS

As the expertise of industrial microwave engineers increases and equipment costs decrease, microwave heating and drying should find wider use in the years ahead. Its speed, quality, and overall economy are major selling points and should encourage repeat orders in many industries. Over 16 finish dryers have been sold to various potato chip manufacturers in the U.S., and comparable repeat orders are expected from the poultry industry. The food industry as a whole seems to offer the most promise for widespread applications of microwave processing as more and more consumers seek ready-to-serve convenience foods. The chemical industry too shows good promise, since microwave curing and filament drying are attracting increasing interest because of their greater speed and economy compared with conventional techniques. In the power industry, feasibility studies have already been made (22) for a high-powered (multigigawatt) microwave power transmission system to supplement existing and proposed EHV (Extra High Voltage) systems. In the communications industry, although much work has already been carried out in the microwave bands, much more will be done in the future, including a possible cross-country microwave telephone system. Industrial applications of microwave energy are just beginning to achieve the widespread interest which should develop into considerable growth for the industry in the coming decade.

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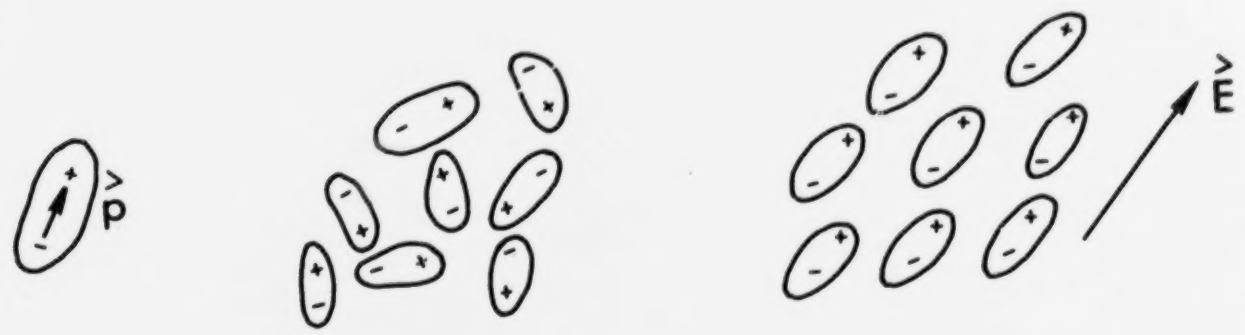
APPENDIX A

PHYSICS OF MICROWAVE HEATING

Because the interaction of radiation with matter often results in heating of the matter, the most widespread applications of microwaves to industry involve rapid heating and drying. The ability of a material to absorb radiation and convert it to heat is determined by its dielectric properties. Some substances, such as water, are able to absorb a great deal of energy, while others, such as metals, reflect rather than absorb the incident energy. Water is an example of a polar molecule -- one which, although electrically neutral, has a dipole moment caused by the net displacement of the positive and negative charge centers. With no external fields applied to a substance made up of these polar molecules, the individual dipoles are randomly oriented and have no net field strength. Yet when an external electric field is applied, as shown in figure A-1, the dipoles absorb energy from the field and align themselves with it.



(a) Net dipole of a polar molecule.

(b) Random orientation of dipoles with no external field applied.

(c) Dipoles lined up with external field.

Figure A-1. Orientation of polar molecules in an electric field.

This energy is stored as potential energy within the system until the external field is removed, at which time the dipoles reorient themselves in a random fashion, transferring their potential energy to heat energy. At microwave frequencies, this process occurs about 10^9 times per second and results in rapid heating.

The above is the basic phenomenon that takes place during microwave heating. Not all substances, however, have the same ability to be polarized. Those molecules, for instance, which have large dipole moments, absorb more energy from an external field during alignment than those with smaller dipole moments. This greater energy storage results in greater energy dissipation when the field is removed and faster heating.

The dielectric constant, K, is a relative measure of the ability of a substance to be polarized (K = 1 for free space). It is tabulated for several common substances in table A-1 below; the larger the value of K, the more energy a substance will absorb from an external field.

Table A-1. Ranges and specific values of K for several common substances[1]

Material	Range/value of dielectric constant, K
H_2O (3 GHz, 25°C)	77.5
H_2O (10 GHz, 25°C)	55.0
Douglas fir	1.8-1.86
Paper, royal gray	2.62-2.75
Steak, bottom round	30-50
Suet	2.5
Soap, Ivory	2.96

[1]From J. R. White, Topics on the Interaction of Microwaves with Matter, presented at the 1968 Varian Industrial Microwave Technology Seminar, January 1968, table V, p. 12.

The table points out the wide range in values of K from 1.8 for Douglas fir to 77.5 for water at 3 GHz, factors which greatly affect the duration of exposure required to achieve a desired amount of drying. The variation of dielectric constant with frequency for such molecules as water will be discussed shortly.

In addition to the dipolar heating described above, many substances display significant heating due to conduction currents in the material. The power dissipated per unit volume in such cases is

$$\frac{P}{V} = \underline{E} \cdot \underline{J}$$

where $\underline{E}$ is the applied electric field strength and $\underline{J}$ is the current density. This heating is identical to the I^2R heating of resistors and is most significant for metals and other conductors. For most of the materials presently under consideration for industrial processing (with the notable exception of electrolytic solutions) dipolar heating dominates at microwave frequencies, and the heating associated with conduction currents can often be ignored.

Two other factors associated with the dielectric properties of a material, which help to describe its behavior at microwave frequencies, are the skin depth and loss tangent. The skin depth[1] is the distance the electric field penetrates into a conductor before it has attenuated to 1/e (36.8 percent) its value at the surface and is given by δ, where

$$\delta = 1/\sqrt{\pi f \mu \sigma}$$

and μ is the permeability of the conductor and σ is its conductivity. The most important feature in this expression is that the skin depth is inversely proportional to both the frequency and the conductivity. In other words, the higher the frequency of incident radiation and/or greater the conductivity of the conductor, the shallower will be the penetration of the wave into the material before the field strength has attenuated to (1/e) its initial value.

In substances with significant polarization, the loss tangent becomes the dominant measure of penetration depth because of the poor conductivity of the material. Table A-2 shows that the dielectric constant, K, of many materials varies with frequency.

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[1] A detailed derivation of skin depth can be found in Reference (6), pp. 249-255.

This arises because the individual dipoles, after absorbing energy from the incident radiation, become oscillators themselves because of the coulomb attractive forces between the separated positive and negative charge centers. These dipole oscillators will absorb the greatest amount of energy when the frequency of the external field is a harmonic of the natural frequency of the molecules.

Table A-2. Ranges and specific values of tan δ for several common substances[1]

Material	Range/value of loss tangent, tan δ
H_2O (3 GHz)	0.157
H_2O (10 GHz)	0.54
Douglas fir	0.027 - 0.032
Paper, royal gray	0.040 - 0.066
Steak, bottom round	0.37 - 0.78
Suet	0.05 - 0.12
Soap, Ivory	0.1765

[1]From J. R. White, op. cit., table VI, page 13.

The above phenomenon can be described mathematically by assigning an imaginary term to the permittivity, ϵ , of the medium; that is, $\epsilon = \epsilon' - j\epsilon''$. The effect of the real and imaginary parts is to account for possible phase differences in the interaction between the incident radiation and the dipole oscillators, allowing stronger coupling when the two frequencies of oscillation are harmonics of each other. The loss tangent is then defined as $\tan \delta = \epsilon''/\epsilon'$. Like the skin depth for conductors, it is an indicator of the penetration depth to be expected in a dielectric medium at a given frequency. Table A-2 shows the loss tangent for several materials currently being processed or considered for processing by industrial microwave equipment. The larger the value for tan δ, the shallower the penetration into the medium. The skin depth and loss tangent point out that as the frequency of radiation increases, more and more of the energy is dissipated near the surface of the material being processed. Materials with low loss tangents and/or large skin depths would most likely require the greater penetration depth of 915 MHz rather than 2450 MHz in order to achieve heating throughout the thickness of the material.

The rate at which microwave energy of frequency f and electric field amplitude E is absorbed by a material of dielectric constant K and loss tangent $\tan\delta$ is given by the expression

$$\frac{P}{V} = 2\pi f K \epsilon_o \tan\delta \, E^2$$

where ϵ_o is the permittivity of free space. The important feature in the above equation is that the power dissipated per unit volume is directly proportional to the frequency, dielectric constant, loss tangent, and square of the electric field strength Since the dielectric constant and loss tangent of a material depend on the material and frequency, the designer of industrial microwave equipment must select the frequency of operation and field strength (power level) so that the power dissipated per unit volume is everywhere small enough to keep the material being processed from becoming singed and ruined by an overly high power density.

In summary, knowledge of a material's dielectric properties is essential in the design of industrial microwave equipment, both for determination of the proper frequency of operation to ensure adequate heating throughout the substance and for the proper selection of power levels and applicator design so that destructively rapid heating is avoided.

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